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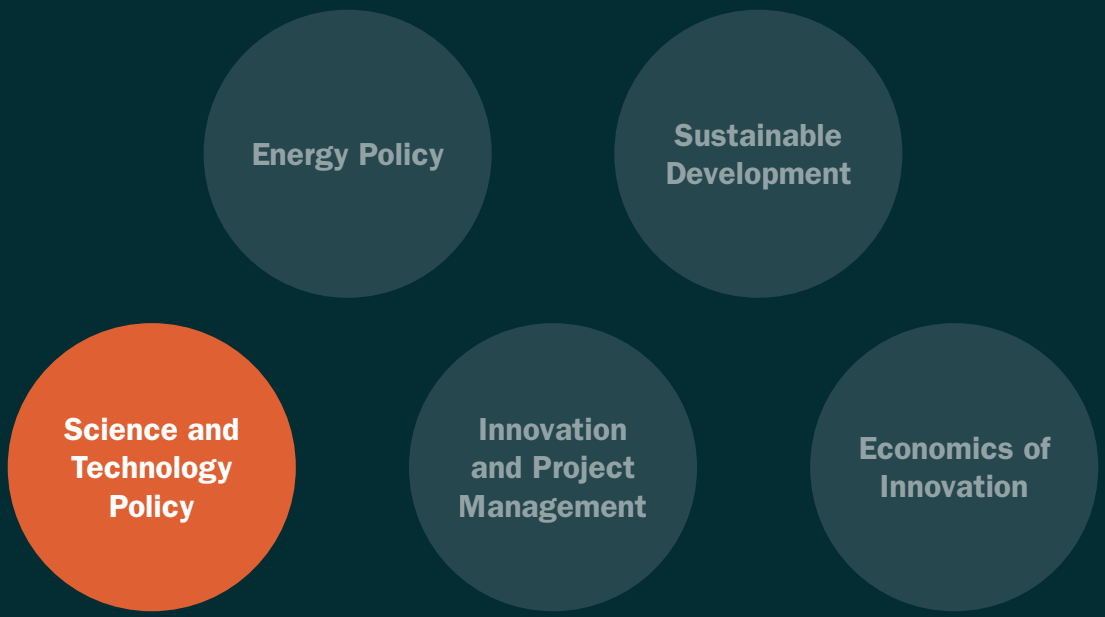

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SPRU Working Paper Series (ISSN 2057-6668)

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The Role of War in Deep Transitions: Exploring Mechanisms, Imprints and Rules in Sociotechnical Systems

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Abstract

This paper explores in what ways the two world wars influenced the development of sociotechnical systems underpinning the culmination of the first deep transition. The role of war is an underexplored aspect in both the Techno-Economic Paradigms (TEP) approach and the Multi-level perspective (MLP) which form the two key conceptual building blocks of the Deep Transitions (DT) framework. Thus, we develop a conceptual approach tailored to this particular topic which integrates accounts of total war and mechanisms of war from historical studies and imprinting from organisational studies with the DT framework's attention towards rules and meta-rules. We explore in what ways the three sociotechnical systems of energy, food, and transport were affected by the emergence of new demand pressures and logistical challenges during conditions of total war; how war impacted the directionality of sociotechnical systems; the extent to which new national and international policy capacities emerged during wartime in the energy, food, and transport systems; and the extent to which these systems were influenced by cooperation and shared sacrifice under wartime conditions. We then explore what lasting changes were influenced by the two wars in the energy, food, and transport systems across the transatlantic zone. This paper seeks to open up a hitherto neglected area in analysis on sociotechnical transitions and we discuss the importance of further research that is attentive towards entanglements of warfare and the military particularly in the field of sustainability transitions.

1. Introduction: Deep Transitions and war

Deep transitions are "a series of connected and sustained fundamental transformations of a wide range of socio-technical systems in a similar direction" where "examples of this directionality include a move towards increased labour productivity, mechanization, reliance on fossil fuels, resource-intensity, energy intensity, and reliance on global value chains" (1, p.1045). The Deep Transitions (DT) framework combines a focus on 'great surges of development' from Techno-Economic Paradigms (TEP) approaches (2,3) and sociotechnical perspectives from sustainability transitions that use the Multi-Level perspective (MLP). The first deep transition refers to the long-term emergence of industrial modernity entailing continuity between great surges of development from 1771 to 1971 which saw the emergence of "unprecedented levels of wealth and welfare in the Western World" in the post-Second World War era (1, p.1046).

A key point of analysis in the DT framework concerns the role of wars in the emergence of the first deep transition (1,4). The 'fourth surge'[1] (between 1908-1971) constitutes the final wave in the development of the first deep transition which spans both world wars. In the TEP approach, the Second World War is recognised as forming part of a 'turning point', between the 'frenzy' stage towards stability and maturity seeing the full deployment of a high growth mass consumer society coordinated by the mass production paradigm (2,3,5). However, world wars are considered exogenous and are only given limited consideration as a focal point of analysis. As Schot and Kanger point out, the TEP approach "largely neglects the role of exogenous events such as wars" where "the impact of macro-events…[including wars].. on the dynamics of surges warrants closer attention" (1, p.1051).

The TEP framework does refer to the importance of the world wars in influencing far-reaching institutional changes such as the welfare state and the empowerment of trade unions, the mass mobilisation of science, and international institutions (6). In this regard, discussions of world wars in the TEP chime with historical accounts elsewhere highlighting the transformational impact of world wars in influencing widespread institutional change (7–18). However, although accounts of the fourth surge identify important developments in the domains of energy, food and transport (see table 1) including new technologies, industries, and infrastructures, there is limited attention regarding how transitions in these areas came about and connect with the wider paradigmatic shifts identified in TEP accounts, and particularly how they were affected by war. Thus, a connection between transitions in technologies, industries and infrastructures and these far-reaching institutional developments is generally underdeveloped, both with regards to the TEP and wider historiographies that tend to be focussed on social or political systems (19).

This is where the other theoretical strand of the DT framework comes in. Drawing on the MLP and a focus on sociotechnical transitions, the DT framework places more emphasis on how developments in domains including energy, food, and transport are pivotal in the emergence of great surges of development. However in the MLP framework, war is characterised as an 'external shock' and remains largely unexplored in terms of the influence on sociotechnical systems (20–23). We address this research gap, asking the central question: what is the role of the world wars in the development of sociotechnical systems underpinning the first deep transition?

Table 1: The fourth surge from 1908: age of oil, the Automobile and Mass Production in the USA and spreading to Europe

	New technologies and new or redefined industries	New or redefined infrastructures	Techno-economic paradigm 'Common-sense' innovation principles
The fourth surge from 1908: age of oil, the Automobile and Mass Production in the USA and spreading to Europe	Mass-produced automobiles Cheap oil and oil fuels Petrochemicals (synthetics) Internal combustion engine for automobiles, transport, tractors, airplanes, war tanks and electricity Home electrical appliances Refrigerated and frozen foods	Networks of roads, highways, ports and airports Networks of oil ducts Universal electricity (industry and homes) Worldwide analog telecommunications (telephone, telex and cablegram) wire and wireless	Mass production/mass markets Economies of scale (product and market volume)/ horizontal integration Standardization of products Energy intensity (oil based) Synthetic materials Functional specialization/hierarchical pyramids Centralization/metropolitan centers–suburbanization National powers, world agreements and confrontations

However, undertaking an exploration of this question requires opening up the 'black box' of the external landscape events of World War I and II, in terms of understanding in what ways these two wars may have influenced sociotechnical systems in ways that were different to peacetime. The need to open up the black box of the exogenous and external periods of world wars can be understood by turning attention to the definition of

[1] The dates of the fourth surge are based on the invention of mass production in 1908 as the first 'Model T' automobile came out of Ford's factory in Detroit, Michigan (6). The date 1971 signals the beginning of the fifth surge when the Intel microprocessor was announced in Santa Clara, California (3).

sociotechnical systems. In the DT approach a sociotechnical system is defined as a "…configuration of actors, technologies and institutions for fulfilling a certain societal function" (1, p.1045). As Geels also notes, socio-technical systems are defined by "the fulfilment of societal functions" embodying technological artefacts, resources, and materials, and actors that maintain and change the system and rules and institutions guiding activities" (24, p.898). A key aspect of sociotechnical systems is that innovations within the system are driven in part by the solving of problems in delivering societal functions (25), which generate the search for new sociotechnical solutions leading to innovation (26). The DT framework similarly argues that the first deep transition emerged from the second half of the 18th century and unfolded in response to pressing societal challenges related to the delivery of meeting societal needs influencing change in sociotechnical systems, while producing new problems which influenced the emergence of a crisis in the first deep transition in the 1970s (4). These two points – the function of sociotechnical systems and change in sociotechnical systems being partly generated by problem solving – are affected by conditions of war.

These two world wars were 'total wars' (27–33) where rather than conflict being confined to a dedicated military, large parts of industry and society are mobilised as part of the war effort. As Van Creveld writes, total war demanded the efficient control of entire systems, where "war itself extended its tentacles deep to the rear, spreading from the trenches into the fields, the mines, and the factories" (34, p.164). Thus, the directionality of sociotechnical systems in terms of their function were reoriented towards wartime imperatives. These wars were on a much larger scale to previous wars, were reliant on immense fire power and industrial resource, and entailed changing conditions of bombardment and disruption which generated unprecedented problems and challenges (31,35,36). Thus, for industry, engineers, policy makers and scientists involved with particular sociotechnical systems, the 'environmental' conditions (37) or 'working world' (9) in which they operated was radically different from peacetime. In conditions of total war, 'civil' sociotechnical systems were entirely enmeshed within the omnipresent system of the war machine which spread its tentacles into every nook and cranny of the economies and societies of belligerent nations. Yet, what the influence of the conditions of total war was on the sociotechnical systems of energy, food, and mobility and the culmination of the first deep transition, both in terms of the specific time period of each world war and longer term change, remains under-examined.

To address this point, we conduct an interpretive analysis based around the development of a novel conceptual approach. The conceptual approach is based around three stages: *mechanisms of total war* from historical literatures (14,32) to understand in more detail how energy, food, and transport were affected during wartime; notions of *imprinting* (38) from organisational studies to assess the extent to which the particular environment of total war influenced subsequent developments in each sociotechnical system in peacetime; and, building on the first two stages of the analysis we discuss the role of these wars in influencing the development of *rules and meta-rules*, integrating our analysis back into the DT framework. We review key literatures to build this analysis that offer different entry points into the precise topic of world wars and sociotechnical systems. This includes literatures focussed on historical accounts of particular technologies and innovations relevant to each system (39–43); more general themes including institutional and political transformations occurring as a result of the world wars (13,44,45); mass mobilisation in total war (27,29,46–48); the role of science in war (9,18,49–52); accounts focussed both on the European (53–57) and North American context (27,46,58–60); and important transnational spaces and developments (61,62).

It is worth noting upfront that this paper does not attempt to present a definitive account of how these three sociotechnical systems were influenced by the world wars. This would be a foolhardy endeavour given that there are entire books and indeed historical fields focussed on a particular war or the particular wartime experience of a single country. The aim of this paper is to open up discussion of a notable research gap (the impact of 'external' or 'exogenous' total wars on sociotechnical systems) and fill in a particular part of the puzzle of the overall DT framework. Given the hitherto underexplored nature of this particular topic in sociotechnical transitions research, this paper seeks to contribute and open up new directions of research rather than providing a complete account of this far reaching topic. Conceptually, this paper also contributes to unpacking the residual landscape category of the MLP, and beyond sociotechnical transitions offers an account of institutional change influenced

by war that is rooted more in the material, technological, and logistical challenges of war rather than prioritising grand narratives based on social or political systems (1).

The paper proceeds as follows. In section 2 we discuss how war has been characterised in TEP and MLP approaches that underpin the DT perspective as well as related literatures on innovation, science and technology. In section 3 we discuss our methodological approach and how our research followed an approach influenced by 'systemic combining' and an abductive perspective tailored to the particular research question regarding the effects of total war on sociotechnical systems. Section 4 focusses on an empirical narrative regarding broad developments across the transatlantic zone in relation to the two world wars and the sociotechnical systems of energy, food, and transport outlining both the degree of persistence of war time imprints, and the role of the wars in influencing the development of rules and meta-rules. We conclude with a discussion of our key findings and further points of discussion, highlighting the importance for sustainability research of confronting the enduring influence of war and the military on sociotechnical systems.

2. War in Techno-Economic Paradigms and sociotechnical transitions

In this section we briefly discuss how war has been considered in TEP and MLP approaches and related fields. With regards to TEP, Perez notes that the Second World War played a key role in the initiation of the fourth surge where which saw manufacturing for this increasingly motorized war "…fully utilis[ing] and expand[ing] the potential of the installed mass-production paradigm" (2, p.126). World war also served as a "dress rehearsal" for state intervention and state-industry collaboration where "the policies of the welfare state were fully accepted" in the post war period. The Second World War is therefore considered part of the 'turning point' which is said to have begun with the Green New Deal in the USA in the 1930s turning a period of 'frenzy' into one of 'synergy' and 'maturity' with an unprecedented period of rapid and stable economic growth in the transatlantic zone until the 1970s (2). Elsewhere, in a discussion of 'K-waves', Coccia (63, p.287) highlights that warfare "…generates huge demand-side effects and powerful supply-side effects" that are pivotal in the rapid diffusion of new technological innovations, building on ongoing debates in this field where hegemonic wars have been analysed both as a cause and consequence of economic fluctuations (64). This focus on 'demand-side effects' and 'supply side effects' in work related to TEP approaches offers a useful launching off point in turning attention towards the particular pressures that are exerted on sociotechnical systems underpinning the 'fourth surge'.

In more historic accounts of sociotechnical transitions drawing on the MLP, wars and the military are only given limited attention in terms of being important in stimulating the use of certain technologies and shaping technological trajectories (65–67). However, often the world wars are discussed as temporal markers highlighting important changes *before* and *after* war, however the role of war in initiating these discontinuities are not explored (68,69). Thus, the world wars are 'black boxed'. Indeed, war is often mentioned in passing as a key example of a landscape 'shock' (20–22,66,70) but the dynamics of sociotechnical change during these shocks remains unexamined. This lack of attention to wars, is part of a broader trend where landscape factors are generally residual in MLP-based analysis of sociotechnical change, and the main focus of attention is on niche-regime dynamics (71). Figures 1a and b point to where war is situated within both the MLP and the TEP, predominantly as an external landscape shock in the MLP, and as an exogenous event contributing to a turning point in TEP. However, to begin to understand the role of war on sociotechnical systems it is important to develop and understanding of how the dynamics of wartime differ from peacetime.

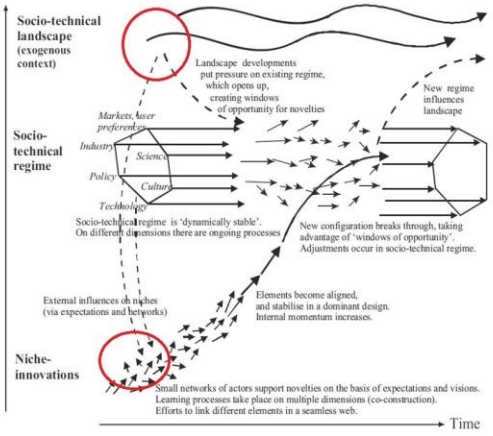

Fig.1a: war and the military in the MLP

Source**:** Geels 2011 (20)

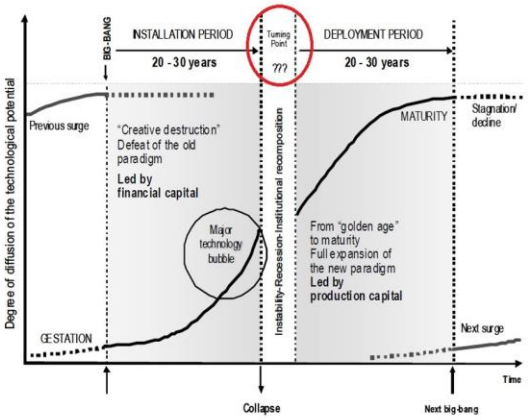

Fig.1b War and the military in TEP

Perez, 2007 (72).

One promising starting point is found in earlier accounts of the MLP, where the key role of war in sociotechnical change was recognised and specific reference made to the different 'environmental' conditions of wartime. Rip and Kemp outline that:

> "Many so-called technological breakthroughs were achieved in wartime…the technological variety on which to build was often already available and is sometimes developed in niches (e.g., polymeric materials before the Second World War), but a different kind of selection environment was necessary"(37, p.362).

Rip and Kemp go on to point out that 'science push' and 'demand pull' are not sufficient to explain technological breakthroughs but that it was their "…mobilization and recombination that allowed the radical innovation." (37, p.362). This point implies that what is crucial to the development of the particular innovation or niche in question is the radically changed *environmental conditions* experienced during wartime that created an entirely new selection environment. However, despite recognition of the pivotal effects of wartime on technological breakthroughs, these ideas were not explored further in MLP accounts of sociotechnical change.

However, looking beyond the MLP to some of the theoretical areas on which it builds such as Science and Technology Studies and innovation theory, there has been notable attention towards the different dynamics experienced during wartime and the effects this had on technological developments. A key example is the work on Large Technical Systems where Hughes highlights how the First World War and the immense pressures to sustain adequate electricity supply shaped the development of large electricity grids (73). In an analysis *Atlantic Automobility* Mom offers a detailed account of how the search for solutions to the particular logistical challenges in keeping the front lines adequately supplied during the First World War had important effects on the development of the automobility system (74) Elsewhere, Schot and Rip highlight how the First World War was crucial in the development of industrial modernity in the Netherlands (75). Some of the key concepts often drawn on in research utilising the MLP have focussed on wartime and military influence, including Cowan's study of technological 'lock-in' and nuclear power (76). In innovation theory and evolutionary economics the importance of the Second World War in establishing the conditions for 'big science' and a rapid increase in R&D spend has been discussed (5,49,77–82), as has the enduring influence of the 'Military Industrial Complex' during the Cold War and technological "spin offs" resulting from large scale military research programmes (83–85). In the subfield of the history of science and technology, more materialist accounts of scientific and engineering activity highlight the role of war in stimulating new centrally coordinated 'big science' based around mission-oriented frameworks (9,10,17,19,50–52,86)

We build on these more materialist accounts of wartime activity; however, this paper is focussed on broader sociotechnical systems rather than individual technologies, innovations or the role of science and R&D (14). We aim to integrate literatures on sociotechnical transitions with literatures related to wartime activity, to build a more comprehensive approach to understanding the broader effects of total wars on sociotechnical systems and the emergence of the first deep transition. Given the neglect of war in TEP and MLP, to answer this question requires the development of a conceptual approach that is attentive to the specific environmental conditions of total war, understanding the lasting effects of war on sociotechnical systems, and the relationship between these wars and the development of rules and meta-rules, integrating our research with the overarching DT framework. We now discuss the development of this conceptual approach.

3. Methodological and conceptual approach

3.1 Interpretive analysis and systemic combining

The question of the influence of world wars on sociotechnical systems presented several challenges. These challenges were central in guiding the search for literatures outside of TEP and MLP approaches which contributed to our conceptual framework. The first challenge was that there was no existing analysis of war at the level of sociotechnical systems. Accounts of the transformational effects of World Wars tend to focus on broader social, economic, institutional and political developments (44,45,87–92), developments related to science and warfare (9,93–96), or particular national mobilisation efforts and their transformational effects (27,29,46,47,97). On the other hand, there are more particular histories focussed on a specific technology or 'sub-system' (such as the car or oil), that included important developments during wartime (98–102). Thus, in order to build a system-level analysis (that takes in to account various industrial, technological, economic, policy and political developments), it is necessary to draw on and combine insights from these different entry points. A second challenge was the need to understand the specific dynamics of world wars and how these differ from peacetime, given that Rip & Kemp amongst others have highlighted that war influences sociotechnical systems in ways that are very different to peacetime, however the dynamics of war are not discussed in detail. A third challenge relates to the most suitable conceptual focus for interpreting continuity and discontinuity in terms of how sociotechnical systems had changed as a result of war.

These challenges guided the development of a conceptual framework, and thus the approach undertaken in this paper can be understood as a process of 'systematic combining' (103,104). Here, the usually hidden road blocks and turning points in the research process have been vital in guiding both strategy for collecting and analysing key literatures, and the emergence of a conceptual approach. As Dubois & Gadde (103, p.559) outline, "the original framework is successively modified, partly as a result of unanticipated empirical findings, but also of theoretical insights gained during the process". This seemed the best approach, given that there was no prior framework available to answer our particular research question. Thus, our research did not follow a linear model whereby a conceptual framework was established and applied, but rather was a process where through a series of different stages of literature review, a conceptual framework emerged that could fit and contribute to our research question. In keeping with the evolving DT framework, the approach of this paper can also be understood as a form of 'appreciative theorising' where the conceptual framework is a 'tool of enquiry' that bends to fit the problem (1).

The first stage of this process was to find a 'way in' to sociotechnical accounts of the world wars. Keyword searches for individual technologies and the world wars – rather than searching at the level of an entire sociotechnical system – produced relevant historical accounts. This included accounts of the historical development of the car, the canning industry, and the oil industry in the 20th century, that included sections dedicated to wartime developments.

Drawing on the DT framework's attention towards directionality, and in particular emergence, stabilisation and acceleration, we constructed a series of vignette style narratives for developments in various 'sub-systems' (such as nuclear energy, the tractor, airplanes) which were organised by what occurred before the First World War; during the First World War; during the interwar period; during the Second World War; and what occurred in the post Second World War period. A further organising principle in these vignettes involved looking at different aspects of a sociotechnical system, including consideration of markets and user preferences, industry, science, policy, culture, and technology (4). The vignettes highlighted both the breadth and diversity of potential impacts the World Wars had on specific technological trajectories.

The findings of these vignettes were presented and stress-tested at a workshop held in June 2018 attended by 16 leading academic experts from security studies, history, and STS. A *world café* format session took place during this workshop, structured around group discussions on the impacts of world wars on energy, food, and transport, which identified gaps in our existing accounts. We obtained recommendations of further examples to consider and further literatures to consult, including the effects of 'total war' which became important in structuring our analysis. The research which followed this workshop led to further reading on notions of 'mechanisms of world wars' which provided a useful framing device for understanding how total wars differ from peacetime. These mechanisms were adapted to analyse and organise empirical examples of wartime developments relevant to the three sociotechnical systems.

Through additional reading around continuity and discontinuity in technological, organisational and institutional change, the approach of imprinting was discovered which seemed a more appropriate fit for the task at hand compared to notions of 'lock in' or 'path dependency' which we explain in the next section. Overall, a large corpus of literature had been gathered (N 160) that approached the topic from different entry points bridging between particular technological developments and industrial, institutional, and political developments to construct system-level accounts. The different kinds of literature used can be loosely summarised as follows: historical accounts of the development of particular technologies during relevant time periods; historical literatures focussed on the events of the two world wars; transformations resulting from wartime focussed on the welfare state and other social and political issues; historic literatures on particular countries and their wartime mobilisations, and additional resources including online archives. Wherever possible, reference to official policy documentation was also used contributing to the plausibility of our interpretive analysis.

Finally, the two-stage accounts of sociotechnical change in energy, food and transport based on mechanisms of war and imprints, formed the basis from which we propose a series of rules and meta-rules and how the world wars influenced their development, integrating our analysis into the DT framework. The overarching research question was developed through the different stages of analysis discussed above, underpinned by three sub-questions as follows:

- **What is the role of the world wars in the development of sociotechnical systems underpinning the first Deep Transition?**
    - How were sociotechnical systems impacted by mechanisms of total war?
    - What lasting imprints did these wars have on sociotechnical systems?
    - What is the role of these wars in the development of rules and meta-rules in sociotechnical systems?

We now discuss the different conceptual building blocks that we use in more detail.

3.2 Conceptual lenses: mechanisms of war, imprints and rules

3.2.1 Mechanisms of total war

During the First and Second World Wars, entire economies and societies, rather than just dedicated militaries, were mobilised and directed towards the pursuit of victory. This is recognised as a condition of 'total war' (27–34,105–107). Here, the theatre of decision making moved from the battlefield to the home front and the lines between soldier and civilian became blurred (58). Recent analysis of the transformational effects that total war had on welfare systems (14), identify a number of 'mechanisms of war' (29) which we adapted to align more closely with sociotechnical perspectives. The four mechanisms discussed below are not the totality of mechanisms identified by Obinger et al. however these mechanisms were selected on the basis of their applicability for examining change related to different aspects of sociotechnical systems. Four mechanisms of war were selected: demand pressures and logistical challenges; directionality; new policy capacities; and cooperation and shared sacrifices.

Demand pressures and logistical challenges

In historical literatures, demand side pressures in the war preparation phase include significant pressures to ensure there are sufficient numbers of healthy and adequately skilled people that can be recruited for wartime activities (14,108–110). From a sociotechnical system perspective, the two world wars created exceptional demands for the supply of energy, food supplies and transport services for war activity. Different forms of transport were crucial in both conveying these key resources to the theatres of war and in the conduct of war itself. The key challenge of maintaining adequate supplies to fulfil particular needs during war, and being able to move and distribute them across the conflict zone presented particular sets of challenges, which extended to defending against attack and sabotage. As a result, the first mechanism of war through which we considered the empirical evidence was whether, how, and to what extent were demand pressures and logistical challenges on socio-technical systems were exacerbated by the two wars.

Directionality

The unprecedented nature of war, Orbinger et al point out, can also change the power resources in politics, society, and industrial relations. For example, trade unions increased their bargaining position through the essential role those they represented played in the war effort (111) and previously marginalised groups such as women were called upon to contribute to the war effort with resulting changes in gender relations in post war policy (8). Whilst these changing relationships have been discussed in relation to post-war social policy, when applied to socio-technical systems, it can also be posited that war may make the position of certain sub-systems within a particular socio-technical system susceptible to change. Rip & Kemp (37) for example suggest that in the search for 'solutions' to pressing demand challenges certain technologies may 'break through', whilst weaknesses in certain technologies or dominant practices may be exposed by wartime logistical challenges. This idea of change connects to the focus on *directionality* within the Deep Transitions framework (1), and so the second mechanism of war through which we examined our empirical evidence was whether, how and to what extent the World Wars influenced the *directionality* of socio-technical systems.

New policy capacities

The disruption and demand challenges created by the world wars are acknowledged as having necessitated increased levels of state intervention (14,15,45). For example, hitherto unprecedented levels of state intervention were required to coordinate economic activity and direct command and control measures. This in turn necessitated the creation of new institutions to control and coordinate war time activities. As Obinger et al write, "large-scale government intrusion in economic affairs went hand in hand with markedly changed relations between government, business organisations, and trade unions; enhancing the administrative, fiscal and legislative power of the state" (p.19). These wars were fought by nations forming alliances with one another on both sides and required closer collaboration between nations in order to achieve wartime goals. Provoked by the

unique conditions of these two wars it is also recognised that increased inter-governmental channels of policy formation were necessary to, for example, enable the supply of key goods and materials (112–114). Accordingly, the third mechanism of war examines whether, how and to what extent the policy capacities to manage socio-technical systems were affected by the world wars.

Cooperation and shared sacrifice

Another recognised mechanism of total war is the need for "mass loyalty in emergency situations" (14, p.17) to assist in meeting military requirements and stabilising the home front. 'Mass loyalty' also required 'shared sacrifices' enacted most obviously through the policy of conscription; rationing of key resources; and curtailment of certain activities and social practices. To realise the singular goal of victory, much of society was influenced and permitted/accepted the required sacrifices (90). Both wars saw hitherto unprecedented levels of collective coordination and pooling of resources and information between actors who were formerly in competition with one another (46,115). In terms of sociotechnical systems, this fourth lens allows for reflection on whether, how and to what extent, cooperation and shared sacrifice influenced changes in our three sociotechnical system of food, energy and transport.

3.2.2 'Imprints' of war

In order to understand the lasting influences of the wars on our sociotechnical systems, we draw on the concept of 'imprints'. The term is widely used in biology and psychology referring to a process where humans and animals are exposed during a sensitive and restricted period of their development to certain external stimuli which influence patterns of behaviour long after the particular period of time has ended. In organisational studies, imprinting has been used to study how industries, organisations and networks (116) continue to reflect the conditions of particular sensitive periods, usually those that exist during their formation, where the organisation continues to reflect core features of that time period such as technological, institutional or economic context. It has also been applied at the meso-level to understand why jobs and occupations often reflect the "circumstances of their creation" (38, p,198), as well as micro level imprints for example how individuals carry early career experiences with them as they move between different organisations and employers (117).

There are three key components to considering imprinting as summarised by Marquis and Tilcsik (38):

> (1) the existence of a temporally restricted sensitive period characterized by high susceptibility to environmental influence;
>
> (2) the powerful impact of the environment during the sensitive period such that the focal entity comes to reflect elements of the environment at that time; and
>
> (3) the persistence of the characteristics developed during the sensitive period even in the face of subsequent environmental changes.

In our case, the conditions of total war between 1914-1918 and 1939-1945 represent the time-sensitive period under interrogation which we examine through mechanisms of war discussed above. Marquis and Tilcsik highlight how imprints can be identified in terms of technological, economic, institutional, political, and regulatory factors, which compliments a sociotechnical approach. The authors also point out that more work is need on exploring 'multiple sensitive periods' which we do in this paper by looking at both the First and Second World Wars and the dynamics of imprinting taking place over the period of the fourth surge.

Imprinting research is well-suited to the DT framework. First of all, it is rooted in biological metaphor similar to deep transitions. The concept has flexibility in terms of focussing on multiple levels (e.g economy, technology) at which imprinting can be studied meaning it can be usefully applied to the different aspects of socio-technical systems. Imprinting research in organisational studies draws on institutional theory and is often focussed on how

certain routines become established and persist beyond the time-sensitive period, and this focus on routines chimes with the focus on rules in the DT framework discussed below. Additionally, imprinting seems especially suited to our empirical focus, where STS scholars have discussed "imprints of military influence" (118) and of course how the horrors of wartime 'left strong imprints' on populations influencing demands for social change (14). Indeed, "war casts a long shadow on peacetime" (119) and the persistent effects of military imprints on particular technological innovations (120) institutional changes, and the formation of political organisations is recognised (114,121), but this has not been considered with regards to sociotechnical systems.

Of course, there are other theories which assess how particular events or historical contexts can have lasting influence on sociotechnical systems however we concluded that imprinting was the most appropriate for our research question. One key reason why imprinting may be a more appropriate notion to understanding the lasting effects of war compared to 'path-dependency' (122,123), 'lock in' (124–127) or 'momentum' (128,129) is that these approaches are more focussed on the evolutionary sequence of events from an initial, often accidental, event, or particular economic and technological factors around sunk costs and 'entrapment' (130,131). Neither of the world wars can be seen as accidental. What is more, rather than tracing the sequence of events following a particular moment in time, imprinting offers flexibility for a more parsimonious matching process. Here, the focus is on looking for similarities between the characteristics developed during the sensitive period through the lenses of the mechanisms of war and the identification of similar patterns including direct reference to wartime influences in post war developments. This process does not rely on extensive sequential narrative accounts and is more appropriate for capturing the breadth of change across three sociotechnical systems. Following Tarquis and Tilcsik, we build an interpretive account regarding whether imprints can be best characterised as having *decayed, persisted or were amplified* during and after the world wars. This brings us to the third building block of our conceptual approach which re-integrates discussions of mechanisms of war and imprinting with the DT framework through a discussion of rules and meta-rules.

3.2.3 Rules and Meta-rules

Rules are defined as "humanly devised constraints that structure human action, leading to regular patterns of practice" (1, p.1053). In the DT perspective, an important distinction is that between rules which are a single rule in a single system, and meta-rules which are single rules in multiple systems. The concept of rules is central to institutional perspectives in the MLP and sociological literatures (132). Rules can have both a constraining and enabling effect on behaviour in a particular system. As Schot and Kanger point out, an important aspect of rules is their "generalisability and transposibility" meaning they can present themselves in a variety of domains including technology, industry and policy. Rules can be informal or formal. In an account of the integration of Europe through technocratic internationalism Schot and Kaiser highlight how the role of "…formal and informal rules that guided experts' behaviour and defined normative expectations" (133, p.39).

An example rule given by Schot and Kanger is "The drive to optimize fuel efficiency" in transport, and a meta-rule (a single rule present in multiple systems) is "an imperative to use fossil fuels" (1). We identify rules by looking at patterns of development in the three sociotechnical systems through the lens of mechanisms of total war and the extent to which there was persistence or decay of certain trends into peacetime in terms of imprinting. From this analysis we propose potential rules and meta-rules present in the first deep transition and the role of war in the evolution of these rules.

3.2.4 Limitations to method and adoption of conceptual lenses

Due to language constraints, we recognise the analysis below at times has a bias towards US-UK experiences of the world wars. War time experiences of course varied considerably between different countries across the transatlantic zone. Further research is required on these experiential variances for further corroboration that the proposed meta-rules can be detected in different locations. Special emphasis should be given in future work to deepening and incorporating system perspectives from Axis countries so that this is not another history from the victors' perspective.

Relatedly the Deep Transition project's primary geographical lens – the transatlantic zone - excludes the geographies of colonialism. Especially in the First World War, the food and energy systems that resided in non-transatlantic countries (e.g. the colonies) were of pivotal importance for countries such as the UK. However, their narratives are currently neglected and should be considered in future work.

A third current limitation in this work concerns causality. To be clear, this paper is not explaining whether a certain phenomenon was caused by the wars or wartime activities. At points we have noted that rules and meta-rules appear during the wars that impinge upon a sociotechnical system but in doing so we do not suggest that the rule in question was caused by the war. Indeed, when, where and how the rules identified in this paper may have initially emerged is a question requiring further research.

In keeping with the experimental and currently evolving nature of the DT framework, we echo Schot & Kanger (4) in pointing out that the approach conducted in this paper should not be seen as a claim to a definitive theory or explanation regarding the role of the world wars in the development of sociotechnical systems. On the contrary it is just the beginning. We see the value of this research in "provoking new ways of thinking and opening up new directions" (4) regarding a hitherto neglected area, which should open up further questions.

4. Exploring mechanisms and imprints: a narrative account of sociotechnical change and effects of the First and Second World War

We now focus on our interpretive account of how the sociotechnical systems of energy, food and transport were influenced by the two world wars across the transatlantic zone and what lasting changes can be observed. Following this discussion of the influence of mechanisms of war on the three sociotechnical systems and a discussion of imprints, we then set out propositions regarding the influence of these wars in the evolution of rules and meta-rules as part of the DT framework.

4.1. The First World War

The First World War has been described as a 'shock' in that many countries had mobilised for a war that was expected to last a few months which turned into a conflict lasting four years (110,134). Thus, the period where nations were actively preparing for major conflict is generally thought to be shorter than that for World War Two (107). The scale of the First World War was at the time unprecedented in terms of its geographical spread, numbers of soldiers involved and the 'industrial' nature of the conflict (135). We now look at how the three sociotechnical systems were affected by mechanisms of war and post-war imprinting dynamics.

4.1.1 The First World War: energy, food, and transport and mechanisms of war

The First World War had a profound impact on all three sociotechnical systems. The shock it created saw immense **demand pressures and logistical challenges** being exerted. The huge demand for oil and petroleum products in this 'machine war', including to fuel tanks, automobiles, planes, submarine and naval vessels, and for the lubrication of machine guns, saw immense challenges placed on oil production (136,137). Meanwhile, coal industries and export routes were severely disrupted in continental Europe, including coal exports from the world's main coal producer, the UK, (138,139). As industrial production increased, maintaining reliable supplies of electricity to fuel production for this 'industrial war' became another key challenge (42,140,141).

Europe's pre-war extensive reliance on imports to feed their populations was severely disrupted by the First World War (142,143). Direct action to disrupt the food supply system included Germany declaring the waters around Britain a 'war zone' which both enemy and neutral vessels entered at their peril in February 1915; German U-boats targeting merchant ships in the Atlantic from 1916 and then declaring unrestricted warfare in 1917; and Britain conducting a merciless blockade of food stuffs to Germany and then to countries occupied by Germany which became steadily more effective as the war progressed. Additionally across Europe, the food production system was hit by labour shortages as men left the land to fight, either voluntarily or through conscription (144,145). With pre-war food supply routes disrupted, there was an intense pressure to increase indigenous food production, alongside an increased demand for US agricultural produce (146,147). Meanwhile, transporting armaments, soldiers, raw materials, and food supplies to the frontlines placed great pressure on rail networks and the need for refined organisation of transport flows in what was a 'war by timetable' (148). The logistical challenges and disruptions to rail supply in both Europe and North America saw a greater military demand for the use of trucks and automobiles (149), and the need for reconnaissance and experimentation in new strategies of air bombardment created considerable demand-pull effects with regards to aircraft industries (100,150).

These demand pressures and logistical challenges influenced the **directionality** of sociotechnical systems. The First World War accelerated the production and use of oil while the war had destabilising effects on the coal industry (151,152). While coal production decreased during the First World War (51), overall production of oil grew by 50% during the course of the war (153) and 90% of allied oil was supplied by the USA (153). By the latter stages of the conflict, oil was recognised to be a key strategic resource on which military prowess depended which became especially apparent with the oil crisis of 1917 (99). Navies transitioned from coal-fired to oil-fired ships, perhaps most notably the UK, which at the time had the largest navy in the world (154). Peak coal production in the UK was reached in the UK in 1913 (155). During the war, significant weaknesses in the coal industry were exacerbated by the war, including labour unrest and lack of mechanisation of the industry (138). The destabilising effects of war on the coal industry were not confined to the UK. Mines across Europe were seriously damaged as a consequence of fighting and near the war's end waves of militancy affected coal industries in Belgium, France, Germany, as well as the USA and Canada (156). Meanwhile, the increased demand for electricity during the war revealed problems with the piece-meal and disconnected nature of electricity supply creating drives for engineering solutions based around increasing interconnection and integration of disparate electricity grids with increasing reliance on larger power plant (42,140,141,156). During the war, world demand for electricity doubled and the electricity industry becoming a large global employer (157).

The war also revealed significant problems with relying on imported foodstuffs, and saw a strategic opening in some countries such as the UK for the importance of intensifying domestic agricultural production and, in the context of a depleted labour supply, the introduction of labour-saving devices onto the farm such as the tractor (158). In the transport system, the significant bottle necks in allied rail-based supply lines experienced in 1915 saw the increasing use of automobiles and trucks for transportation as well as the construction of the 'world's first highway' by the French (74,159). Automobiles were also seen as pivotal to victory for example at the Battle of Verdun (74). In the USA, logistical issues with rail transportation were also experienced and caravans of trucks were utilised to transport key materials to ports for shipment to Europe (160). The First World War saw a rapid

increase in demand for aeroplanes for reconnaissance operations, air battles, and limited bombing campaigns, leading to the emergence of large aircraft industries which had been in an 'embryonic' phase at the beginning of the war (100,150).

Across all three systems **new policy capacities** emerged to deal with the intense logistical challenges presented by the war. Belatedly, once the shock of the war not ending within months had subsided, states intervened and created national policies and/or new political positions charged with directing systems. In the USA the position of 'Energy Tsar' was created to coordinate oil supplies (99), and in each of the major belligerent countries specialised agencies were created to manage coal supplies (139). In the UK this included the partial nationalisation of the coal industry and its classification as a 'Scheduled (or reserved) Occupation' in 1916 (56,138). Across belligerent countries, new central government posts were created to oversee their respective food production and distribution systems (161). This included intervening to guide economic activity via centralised pricing guaranteeing or fixing as well as production interventions. In Germany, first the local and then the central authorities' prices were initially capped for staple products such as milk bread and potatoes, all normally provided through imports and then fixed as the Allied blockade on good began to bite.

In the UK, a system of guaranteed minimum prices was set under the Corn Production Act of 1917 and likewise after entering the hostilities in April 1917 the US government also attempted to guide economic activity via centralised price and production interventions. In all major belligerent countries new central government posts and/or departments were created to oversee their food production and distribution systems. In Britain, the Ministry of Food Control was established in December 1916 with Lord Devonport, and later Lord Rhondda, as Food Controller. In the US, Executive Order 2679-A established the US Food Administration appointing the future President Herbert Hoover as the United States Food Administrator in the newly created government department, the Food Administration (146). Each of these newly created capacities devised and oversaw systems to induce change in farming productivity including incentivising mechanisation. In the US, farmers were offered support to do this via the Federal Loan Act in 1916.

In the transport system, the automobile, which had previously been associated with a certain 'anarchy' and lack of regulation, became more tightly controlled as the French military centrally coordinated traffic flows and developed a 'systems' approach to managing the 'swarm' of automobile traffic (74). This centralised approach was adopted by the British and then the USA (74). Rail transportation became directly controlled by the Government in the UK with the creation of the Railway Executive Committee, and in the USA in 1917, the Government took control of the rail network under the Federal Control and Possession Act (162).

New international policy capacities also emerged to attempt to deal with challenges related to transferring resource from North America to Europe, including the Inter-Allied Petroleum conference in 1918 to coordinate the supply of oil from the USA to France and the UK in response to the oil crisis of 1917 (163). The Inter-Allied Aviation Committee between France, the UK, Italy and the USA was established to standardize aircraft design and maintain adequate levels of industrial production and supply of key components (164). Meanwhile, Europe became increasingly dependent on US agricultural produce to maintain food supplies (110).

In terms of **cooperation and shared sacrifice**, wartime logistical challenges saw closer collaboration between private oil firms and policy makers (165). Indeed, the American oil industry responded to the challenges of the 1917 oil crisis successfully, however achieving this "…involved the cooperation of various segments of the industry on an unprecedented scale under the leadership of a committee of experienced oil men" (165). In the electricity sector there was increasing collaboration between privately owned grid operators to work with each other across different grids as well as local grids working with larger power plant operators to maintain supply (42,140). As the war progressed, increasingly interventionist planning and compulsory management activities in the food production and distribution systems were initiated so that "the sacrifices [were] equal."(166). Mass propaganda campaigns emphasising shared sacrifice accompanied the introduction of rationing in the UK changing societal expectations in consumption. In the US and Canada, both geographically distant from the frontline, propaganda campaigns compelled farmers to increase production in agriculture and to frame changed

eating habits as patriotic actions (167,168). Meanwhile, in the transport system industry cooperated with government to align with wartime production goals. Initially reluctant, Ford converted his production lines to the war effort in 1917 producing boats, military trucks, canon and many other war products as well as investing R&D into armoured trucks (169). Activities in the coal industry can be considered somewhat an exception to the general trend towards collaboration, where significant conflict and unrest continued between the trade union movement and government during World War I (156).

4.1.2 Imprints of the First World War

The immediate imprints of war on sociotechnical systems across the transatlantic zone were influenced by the different experiences of scarcity and abundance. In terms of energy supply, the successes of increased production and maintaining a constant supply of oil saw the American oil industry experiencing a crisis of 'overproduction' as the industry was "…unable to settle down and smoothly adapt its production to the new conditions of peace" (163). However, "interaction with the automobile" was the solution to this problem where "the petroleum industry, a prime mover of the war effort, was at the centre of the reorientation of the industrial plant and equipment of the American economy in the build-up and achievement of high mass consumption" (165). A lasting consequence of the war was that oil was considered a key strategic national asset in the minds of governments which would have profound impacts on future developments in the twentieth century. Indeed, The First World War created a "an oil frenzy…which greatly influenced international relations after the war" (153). The demand for oil products during the war and the importance placed on maintaining a constant supply left a lasting imprint on the system regarding the importance of securing access to oil supplies (154,163,170). France, for example, due to the petroleum shortages experienced in 1917, established the Compagnie Française des Pétroles, mainly to build up strategic petroleum reserves after the war (171). In the UK, the Oil Fuel Board was established as part of the Imperial Defence Committee in March 1925 and was served by the Petroleum Department which was an institution which had its origins in the war (172).

The coal industry had been severely disrupted by the war and the industry struggled in the years after the war to reach pre-war production levels. The labour unrest in the coal industry that had been amplified by war-time challenges, spilled over into peacetime across Europe and North America (156). In countries like France much of the coal mining workforce had been killed during the war (156). For the leading coal power, the UK, many considered the industry to be in decline in the years after the war (69,138,155,173) with leading experts accepting in the 1930s that the coal age had now given way to the "oil age" (174). Meanwhile in the USA the expansion of hydro-electric capacity was authorised in direct response to concerns around maintaining supply that had been revealed during wartime and hydro capacity doubling in four years in the USA (175). In France, wartime energy shortages due to disruption of imports and the destruction of its own coal industry, had amplified concerns over energy security, leading to the expansion of hydro-electric power (176).

State intervention continued to some degree in the energy system. Laws on prices of electricity were issued in Belgium (1919), Italy (1919), Spain (1920), and Germany (1922) (55). The engineering responses during the war to the challenge of maintaining electricity supply left a lasting imprint regarding the value of interconnection, the development of more centralised electricity grids, and use of larger power plant for production. A paradigm of centralisation continued to be advocated by some in the electricity sector and the political sphere more generally (42,140,141,177). A mass power survey was proposed in the USA to plan for the integration of disparate electricity grids through long-range powerlines (42), however the survey did not take place until the 1930s. Indeed, despite efforts to integrate both the technical and organisational aspects of the American electricity industry, Cohn notes that by 1940 "…the industry and its thousands of operating parts were still more disaggregated than linked" (42, p.99). In the UK, there was also calls for centralisation and interconnection of electricity supplies to be overseen by a central governing body however this was fiercely contested on ideological grounds after the war (140). Yet, while plans influenced by wartime experience for more centralised state control

of electricity networks dissipated in many countries (141), in the UK the 1926 Electricity Act and the creation saw the National Grid (178) which went some way in implanting a central governing body for electricity production that had been called for by many engineers and policy makers following war time experience (140).

However, many of the state intervention measures taken during the war in the energy sector did not last to peacetime as a return towards a *Laisse Faire* approach to market governance in the 1920s occurred to some extent (179). In terms of international policy capacities however, the strategic importance of oil realised during the war set off geopolitical disputes between the UK, France and the USA concerning access to Mesopotamian oil reserves (163,180,181). This period of friction culminated in intense negotiations around the "As Is" and "Red Line" agreements in 1928 which can be seen as the first attempt towards establishing the international organisation and regulation of oil supplies. This organisation was deemed important due to the risks of 'over supply' that was a consequence of intensive prospecting that occurred in the 1920s. This 'oil frenzy' was partly a result of wartime lessons regarding the importance of securing strategic oil supplies (99,156). The demand challenges and engineering progress made during the First World War regarding electricity supply contributed to increased international collaboration around electricity engineering and science with the International Council on Large Electric Systems established in 1921, and the World Power Conference established in 1923 (182). Under the auspices of the League of Nations, founded as a direct result of the war, increasing collaboration on proposals for an integrated European electricity grid took place in the Committee on Electric Questions (CEQ) at the League of Nations (55), however momentum around these plans had dissipated by the 1930s as a return to nationalism took hold.

With regards to the food system, the demand shocks experienced during the war had divergent effects on different countries. Italy and Germany placed great emphasis on the creation of national food systems and achieving self-sufficiency after the war including through state intervention measures (183). However, in other countries such as the UK and US many of the interventionist measures under-taken during the war were not pursued in its immediate aftermath (184). Rather these resurfaced during the agricultural depression of the 1930s with the creation of market boards with broad powers to regulate production and quality, implement subsidies and other price supports (184) via Roosevelt's New Deal and the 1933 Agricultural Adjustment Act (185). These interventions made responding to a future war easier. Scared by the knowledge that the UK had come "nearer to defeat owing to food shortage than we did from anything else."(186), the British government began planning how it might feed the country if another war broke out shortly after remilitarisation of the Rhineland in March 1936. This resulted in the establishment of an extensive "shadow" organisation for food control (187).

Great divergence between countries can also be seen between those on continental Europe and the USA. Farmland in France and Belgium was utterly devastated by the First World War and there were significant food shortages following the end of hostilities. One lasting imprint with regards to French agriculture was that of farm ownership consolidation (144). Vivier for example notes that French agrarian sector had moved from a sector dominated prior to the First World War by small owner-tenants with less than 10 hectares to one dominated in the 1930s by larger family-run farms of approximately 4-40 hectares (188). This consolidation process was possible due to the tragic reason that many smaller farms were empty following the war due to the high rural death toll. Meanwhile, an immediate imprint of First World War on the USA was the problem of abundance: the First World War had created an 'economic boom' in US farming but as Europe began to recover, demand for US-based produce decreased creating an over-supply problem (146). Many farmers faced bankruptcy as a consequence. Roosevelt's New Deal supported the food production system through its food subsidy programmes. Here, surplus products were redistributed to schools and poor families and the 1933 *Agricultural Adjustment Act* enabled the US government to purchase food directly from farmers and pay farmers to reduce acreage to prevent prices falling further (189).

Strongly influenced by the challenges of providing a sufficient diet to soldiers and their experience of eating rations during the First World War, research into the nutritional content of food accelerated during the interwar period (9). Studies of vitamins, minerals, and their impact on health, alongside policy documents examining food

and nutrition problems were published by Health Division of the League of Nations, the British Medical Association and the US National Academy of Sciences. This led to the drawing up of nutrient recommendations – or recommended daily allowances (RDAs) for protein, energy, and eight vitamins and minerals (190). Research into the use of chemicals for fertilisers also intensified in this period driven by the imprint of the drive to increase domestic agricultural production.

With regards to the transport system, a key imprint in relation to directionality was lasting recognition of the strategic military significance of trucks and automobiles and the need for adequate road infrastructure. Indeed, wartime bottlenecks in truck transportation had revealed road systems as being inadequate for enabling smooth traffic flows. Increasing construction and organisation of road systems occurred to remedy these war-related inadequacies. Wartime experience left a clear imprint on post-war policy in the context of the USA where the mapping from 'point zero' exercise in 1919 in which future president Dwight Eisenhower took part, and the subsequent Federal Highway Act 1921 were specifically influenced around lasting military concerns around inadequate road infrastructure during WW1 (159,191,192). In the UK there was also substantial investment in highway infrastructure following the creation of the Ministry of Transport in 1919 and centralised organisation of a road traffic system, including road signage, speed limits and a highway code amongst other developments (193). However, centralised state support and planning around the automobile generally dissipated by the end of the 1920s across the transatlantic zone. However, highway construction formed a key part of Roosevelt's New Deal and of course Hitler's construction of the autobahn in the 1930s (194), which spilled into mobilisation for the Second World War (192).

Logistical challenges experienced with the railways in the USA and the growing competition from the automobile after the war meant that railways faced a challenging environment of reducing passenger numbers and freight volumes in the inter-war years in many countries (195–197). The war seems to have been a decisive turning point in this trend as noted by Garrett (198)[2]. Meanwhile, the First World War accelerated the emergence of an aircraft industry driven by military demand leading to increased consolidation and standardisation of production which left a surplus of wartime aircrafts and pilots that were absorbed into a new civil aviation sector (199). In terms of international developments, a lasting imprint seems to be the development of increasing regulation around aircraft which has been identified a direct result of the problems experienced in terms of air space infringements during the war (164,200).

The imprints of shared sacrifice and cooperation are in many ways harder to identify. However a general sentiment towards the need for more collective prosperity following the sacrifices made during war time on the part of the wider population can be seen to have influenced developments such as the National Grid in the UK, and a yearning for freedom in the USA following wartime sacrifice was epitomised by the emerging car culture as part of the 'roaring twenties' (201).

4.1.3 Summary: First World War

In summary, we see partial imprinting of the First World War with variation between the three systems, and *decay* in terms of the dissipation of certain interventions, perhaps most notably in the food system with many policies for controlling food supply being withdrawn across the transatlantic zone. The inter-war years were a period of competition – as both the coal and rail industries struggled to maintain competitive edge as the oil and automobiles expanded. However, imprints of the First World War were beginning to be *re-amplified* as war mobilisation began again.

[2] As Garrett notes, "The period of certainty and dominance enjoyed by railways before 1914 were brought to an abrupt end when war broke out in Europe. Until the outbreak of the conflict they had enjoyed something of a "Golden Age". After 1918, the certainty that railways were the profitable premier form of transport was gone for ever" (198, p.22)

4.2. The Second World War

In 1928, Walter Hines, director of the American railroads reflected on the experiences of total war and how wartime imperatives had influenced new forms of centralised control over industry:

> ""When success or failure depended upon the concentration of energy and the mobilisation of every available resource, there was no holding back the extension of government control over the whole field of industry and economy. This was the almost universal lesson…It, therefore, seems reasonable to assume that if war was to come again that lesson would continue to be applied here as elsewhere, with increasing force…"(202, p.xiv).

Walter Hines' prediction was correct. The lessons of the First World War would be built on but with 'increasing force', as now-familiar mechanisms of war that emerged in the first total war between 1914-1918 were re-amplified and intensified across the transatlantic zone.

The Second World War was however different from the First in terms of there being a considerably longer period of mobilisation for conflict, its duration, number of belligerent nations, and theatres of action. The quantitative differences are compared in the table below.

Table 2: Two world wars in quantitative comparison

Two World Wars in Quantitative Comparison		
	World War 1	World War 2
Length of war, days	1564	2194
Number of belligerent nations	33	62
Theatres of military action		
Number of nations	14	40
Number of continents	1	4

Source: Broadberry and Harrison *The Economics of World War 1,* 2005 p35 (110)

Indeed, the scale of industrial production was far greater in the First World War and it has been characterised as a "war of mass production" (203), where industry was mobilised to an unprecedented level.

4.2.1 The Second World War, energy, food, and transport and mechanisms of war

In terms of **Demand pressures and logistical challenges**, disruption of supply routes proved a formidable challenge. In the energy sector, as oil supplies to the UK became cut off by bombardment from German submarines in 1941, a key challenge centred on sustaining constant supplies to Europe from the USA for military forces that were now considerably more oil-intensive than before (40,58,98). For example, in the Second World War American forces in Europe used one hundred times more gasoline in World War II than in World War I (40). With the USA supplying 90% of oil to allied forces, German submarine attacks on Shipments of oil up the American East coast was a point of attack that threatened to jeopardise the entire allied campaign. Meanwhile, the European coal industry and established trade routes such as those from the UK to continental Europe were once again severely disrupted (204). Territorial expansions by Germany, air bombardment of the German coal industry by the allies, submarine warfare, and workforce shortages due to men being deployed to the battlefield were all factors that presented challenges for the coal industry in Europe (204,205). Meanwhile the increased scale of industrial production in belligerent countries to produce the machines of war in unprecedented volumes including munitions, planes, tanks, jeeps, and entirely new activities like nuclear weapons manufacture in the USA, saw an intensified challenge around sustaining adequate supplies of electricity (61,62). Mass disruption of

food supplies across Europe occurred as a consequence of warfare, and there was an increase in demand for North American agricultural produce. In the transport system, the arrival of "mass air war" (206) or "bombing war" (207) entailed unprecedented demand for aircraft production, new infrastructure for air travel and managing and coordinating unprecedented flows of air traffic. To produce the immense volume of war machines, considerable pressures were placed on the industrial capacities of the automotive sector (89).

These demand pressures and logistical challenges affected **directionality** in each system. In response to the bombardments of oil shipments on the East coast of the USA, the "Little Inch" and "Big Inch" oil pipelines were constructed in under a year so as to transport oil and natural gas across the country. These pipelines utilised innovations that had no market prior to the war (208,209). New refineries and oil tankers were constructed to achieve war time production goals (165). In the UK, due to the threats of German bombing of truck-based transportation of oil, an extensive underground network of pipelines was constructed that by the end of the conflict, supplying every air field in England (172,210). Innovations in fuel types, such as high-octane fuels, all-purpose motor fuels and all-purpose diesel fuels, as well as catalytic cracking techniques accelerated developments with regards to oil-based products (120,165,211). Drawing on the experiences of the First World War, the engineering response to the increased electricity demand in both the USA and UK saw the intensification of interconnection, pooling, and increasing centralisation of electricity supply (42). In Canada, war time demand particularly for aluminium production influenced plans for the construction of large centralised hydro-electric plants and transmission infrastructure (59,60,212). And before the war's competition a new source of primary energy had been realised in the form of nuclear fission (213).

In the USA, intensified agricultural practices became increasingly utilised with handicraft and extensive techniques of husbandry replaced to a certain extent by intensive, scientifically-managed continuous production systems, with an increased use of hybrid corns (214). Mechanisation also increased markedly in the USA and the UK agricultural sectors (184,215). In the UK in 1939 there were 56,000 tractors and by 1940 there were 100,000 (216). Developments in nutritional understandings of food and their application also intensified (43), so too the application of new food preservation and packaging techniques making food lighter to transport. In the USA and UK agricultural output expanded and farmers experienced increased profits due to fixed prices (145,217,218). This contrasted significantly with continental Europe however. The differences in food production across the transatlantic zone was one of the most devastating and tragic aspects of the conflict. Food output fell in continental Europe by 40% while in the USA it increased by 50% (218). Millions starved to death in Europe, with starvation being the leading cause of death during the conflict (218)

In the transport system, rapid advancements occurred in terms of the development of aircraft with planes being mass produced for the first time as part of the USA's war mobilisation (217). The war saw the development of larger airframes, standardisation, jet engine technology, radar technologies, air traffic control systems, and a rapid runway construction programme in Belligerent nations (41,149,150,199,206,219,220). The US auto industry was redirected towards the war effort, playing a central role in the mass production of tanks, trucks, jeeps, airplanes, bombs, torpedoes, steel helmets and ammunition under huge contracts issued by government (46,221–223). The British car industry was similarly re-directed towards the production of war materiel (224).

The changed directionality in in each system was predicated on **new policy capacities**. State intervention occurred across all three systems, and often at an earlier stage of conflict than had occurred with regards to the First World War, suggesting again that policy was responding to the familiar environmental conditions of total war (47). In energy, the UK government took total control of the oil industry in 1938, before war had been officially declared (40). In the USA following the attack on Pearl Harbour in December 1941, the position of Petroleum Coordinator under the Petroleum Administration for War was created to enable close 'two way' communication between government and the oil industry to achieve ambitious wartime oil production (40). To achieve wartime goals, there was a marked increase in state investment in oil infrastructure. In 1938, the Coal Act in the UK nationalised coal deposits, and in 1942 all energy supply was brought under the newly created Ministry for Fuel and Power (57). Central coordination of planning around maintaining electricity supply was carried out in the USA and in the UK with the Ministry of Supply working closely with the War Office (140).

In the food system, belligerent countries prioritised maintaining a constant food supply so as to stave off the sort of food shortages which had threatened their effort during the First World War. The extensive "shadow" organisation for food control had been built up in the UK from 1936 included identifying key personnel who could quickly step in to administer a revived system of centralised procurement and rationing (225). When the war finally came in September 1939, and the government achieved expanded statutory powers to take over the economy, it was more ready to handle the accompanying food shortages than it had been for the First World War, one sign being that rationing began on 8 January 1940, only eighteen weeks after the fighting began (225). In Germany, food supply took on a prominent role in Nazi economic policy with both Erzeugungsschlacht (battle for production) and Lebensraum (living space) policies later having devastating consequences (102,226,227).

State intervention in the food production system included, in the UK, the establishment of County War Agricultural Executive Committees who were told on a county-by-county basis by the Ministry of Agriculture and Fisheries “how many thousand acres they are expected to have ploughed up” and empowered to “serve order requiring work to be done, or, in the case of default, to take possession of land (228)”. The Women’s Land Army and the distribution of tracts assisted with the ploughing up of land and farmers were heavily subsidized by the Ministry of Food buying produce at higher prices and selling back to British citizens at lower prices. In the USA, federal intervention was central to ensuring the ‘abundance’ and ‘over supply’ of food (229).

In the UK the Ministry of Transport took control of the railways and the road networks (224). In the USA in 1942, Government intervened and all sales of cars and the delivery of cars to customers were frozen by the Office for Production management (99,221). In 1941, the National Interregional Highway Committee was established to examine the idea of creating a system of highways that would meet the immediate requirements of the War Department and the future needs of increased post-war traffic (192). In 1942 Roosevelt created the War Production Board regulating industrial production and allocation of material and fuels, coordinating heavy manufacturing and rationing of materials. The mass mobilisation of science (9) including a rapid increase in R&D spend had profound effects on the transport industry especially in relation to technologies for aviation fuel, jet engines and cabin pressure (97,102,103). The application of science also influenced the food system. To persuade those on the home front to alter their consumption patterns, psychologists, sociologists, anthropologists, food scientists, dieticians, and home economists were drafted in to provide advice to government departments. The resulting marketing and education campaign focused on women re-envisioning them as ‘quartermasters of their own kitchen’ (168). Perhaps the most infamous mass mobilisation of science that took place during the Second World War was the Manhattan project (230). This would have a profound influence on the sociotechnical system of energy, as before the close of the in 1944 General Groves appointed a committee to look into the possibilities of nuclear fission that were ‘not all destructive’ paving the way for the development of nuclear energy production for electricity supply (213).

The Second World War also saw an intensification of ***cooperation*** and more widespread adherence to the idea of ***shared sacrifice***. In the United States, formerly competing private companies in the oil sector worked closely with each other and shared innovations under a common framework to achieve war time aims (165,210). Pipelines were built that were dependent on oil companies pooling resources and sharing innovations (209). Sacrifice for the civilian population was experienced through the curtailment of gasoline sales, automobile sales and food rationing policies (99,163,225,231–233). In the USA, patriotism and the idea of shared sacrifice dominated the agricultural sector with propagandists relaying the ‘dramatic story of sacrifice’ of labourers working long working hours and farm women and children filling vacant spaces left by sons and brothers (234,235). With regards to the mobility system, the mass mobilisation of the auto industry for the war effort saw close collaboration between competitors, the sharing of innovation assisting in the refining and standardization of mass production techniques and a strong sense of solidarity among the labour force and management which cut across class divisions (46,217,223,236). The curtailment of automobile sales and gasoline sales experienced by the wider civilian population was predicated also on notions of shared sacrifice for the war effort (115,237).

4.2.2 Imprints of the Second World War

Unlike the partial imprinting and subsequent decay of some imprints that occurred after the First World War, the imprints of WW2 occurred across all three systems and persisted for decades. Imprints of war were shaped by the broader differences across the transatlantic zone. To a far greater extent than after the First World War, a key distinction in the immediate aftermath of the Second World War is between a condition of abundance in North America and scarcity with regards to continental Europe. Following World War II the immense productive war machine that had mobilised sociotechnical systems in the USA left a legacy that had "appeared to have finally solved the riddle of scarcity" (238, p.83). However, the conditions in continental Europe were starkly different. Food supply systems had been severely damaged and millions had died due to starvation. Meanwhile, energy and transport infrastructure had also been significantly damaged (218).

The sociotechnical system of energy was transformed by the Second World War. The war had accelerated the creation of a mass infrastructure around oil through the rapid construction of pipelines and refineries (239). This wartime infrastructure had opened up the East Coast of the USA to the supply of cheap natural gas. Indeed, consumption of both natural gas and oil expanded rapidly after the war (240) and by 1951 oil had become the main source of energy in the USA (156). Returning the surplus of government-owned oil infrastructure to civil purposes was an immediate challenge, where the 'disposal of government holdings' saw pipelines, refining capacity, and the 500-ocean going tankers built during the war transferred back to the private sector (165). With regards to future electricity supply in the 1950s, nuclear power became a symbol of modernity and great expectations formed around ideas of limitless abundant electricity supplies and a world of nuclear powered cars, aeroplanes, and urban environments (241). This source of energy that captivated the minds of post-war governments did not eixst in any practical form prior to the Second World War.

In the food system, the rapid intensification in US agricultural productivity during wartime - and remembering the depression which followed the First World War - ensured that post Second World War attention turned towards the problem of managing abundance and avoiding problems encountered due to over-supply following the First World War (218,242). New technologies released during the war such as DDT (243), acceleration in the use of hybrid corn (214), and the acceleration and refinement of the canning industry mastered during the war were shaped the post-war civilian food sector (218). Radar technology developed during the war enabled abundance to be achieved in the fishing industry (244). In the transport system the war left a legacy of new airports, runways, air traffic control systems and new standardised and larger aircraft powered by jet engines and equipped with cabin pressure opening up the era of mass international air travel (220,239). In the USA, the mass mobilisation of the auto industry and successful reconversion of this industry to peacetime, was key to maintaining economic growth and full employment, stabilising US oil production through gasoline sales and avoiding a post-war recession (165).

The USA recognised that stable economic growth in Europe and solving Europe's and Japan's condition of scarcity was crucial for America's continued economic expansion and geopolitical supremacy (245). Europe's emergence from scarcity would be underpinned by the provision of cheap oil from new Middle Eastern sources which following negotiations between Saudi Arabia and the USA during the war, were flows of oil effectively controlled by the United States (163). The increasing demand for oil in Europe after the war was also a result of continued coal shortages experienced in Europe due to the destruction of coal infrastructure and trade routes during wartime (205). The European Recovery Programme initiated by the USA in 1948 facilitated a rapid transition to oil becoming the main source of primary energy in many European countries over the next two decades. Indeed, 20% of the Marshall Plan loans related to the importation of oil to Europe (62). Meanwhile, the value of interconnection, large centralised plant, and pooling of electricity resources had again been a key lesson of total war. A paradigm for electricity supply and consumption based around increasingly large plant and continuous baseload production supplied through centralised grids became stabilised after the war (42,140,246). As part of the European Recovery Programme, information sharing on electricity grid management from the USA to Europe took place and funds were allocated for the reconstruction of grids following war damage. These

reconstruction efforts were influenced by wartime experiences based around the lessons of the value of interconnection and centralisation. The full electrification of society was realised in most parts of the transatlantic zone in the post-war era (42,55).

Many of the new policy capacities that emerged in wartime continued to imprint on sociotechnical systems in peacetime. The Second World War had solidified the key role of the centralised state in intervening in sociotechnical systems (14,84,247). In the UK for example, coal was nationalised in 1947 and electricity supply in 1947 (248); the UK Agricultural Act 1947 established price guarantees, subsidies, and state funding of agricultural colleges and departments of agriculture to carefully steer food supply systems (249). The UK also invested in highway expansion, legislating for the construction of highways in 1946 and under the 1947 Transport Act, large swathes of the railways, road haulage, canals and ports were brought under direct control of the British transport commission (196,250). In France the aero and auto industries were nationalised and Electricite de France (EDF) was created nationalising power supply and overseeing large construction of hydro-electric (251) and later nuclear power (241). While nationalisation was generally not feasible in the USA for ideological reasons, the state continued to play a key strategic role. Eisenhower's Minerals Commission continued to coordinate policies in relation to maintaining oil supply (163). The 1946 Research and Marketing Act created a role for government in finding solutions to the problems of abundance, using R&D and policy expertise to find new uses for agricultural products and discover untapped markets (252). The Food for Peace programme created intimate entanglements between solving the problem of abundance in the US and extending the USA's hegemonic reach in the context of the Cold War (252,253). In the US, the state took a lead role in financing a mass highway expansion with the 1956 National Interstate and Defense Highways Act which transformed the US road system. Here, the design and integration of urban areas and the integration of freeways was shaped by concerns around military mobilisation logistics and planning for nuclear attack (222,254).

A lasting imprint of the Second World War affecting all systems was the 'permanent mobilisation of science' with sustained large R&D budgets lasting until the 1970s across most of the transatlantic zone (86,255,256). Nowhere was this more visible than with the case of nuclear energy, which certain countries pursued for military reasons under the auspices of civil nuclear developments (241,257–259). Emerging from the initial development of military nuclear capability during the war, 'civilian' reactors followed design specifications that enabled 'dual use' functions, for example early British 'civil' Magnox reactors, (260–262), were designed to enable the production of plutonium for weapons in addition to electricity production (263,264). These technological imprints of war and the military continued with alternative reactor designs, such as the PWR reactor stemming from design specifications for nuclear submarine reactors in the US navy (265,266). The policy imprint of close state collaboration between science, the military and industry, became known as the 'military industrial complex' which was a continuation of new coordinated relationships between science and the state that had been forged during the violence of World War II (267).

New international policy capacities emerged from the Second World War to manage sociotechnical systems. At the international level, the United Nations (UN) officially came into existence on October 24th 1945, when the Charter had been ratified by China, France, the Soviet Union, the United Kingdom, the United States and by a majority of other signatories. Article 1 of the Charter's first chapter states that the purpose of the UN is to "maintain international peace and security"; "achieve international co-operation in solving international problems of an economic, social, cultural, or humanitarian character" and to be "a centre for harmonizing the actions of nations in the attainment of these common ends" (114). To that end, many changes were established through the United Nations and new autonomous bodies, such as the Food and Agricultural Organization (FAO) and International Atomic Energy Agency (IAEA) were formed within the UN system to manage the challenges related to the food and energy systems. The FAO, the oldest of the permanent specialised UN agency was established in October 1945 with the objective of eliminating hunger and improving nutrition and standards of living by increasing agricultural productivity. The IAEA, whose genesis was US President Eisenhower's "Atoms for Peace" address to the UN General Assembly on 8 December 1953 (268), was established in 1957 with the dual mandate to promote and control the uses of the atom. A lesser known specialised UN agency, the International Civil Aviation Organization (ICAO) came into being in April 1947 stemming from the signing of the 1944

Convention on International Civil Aviation (Chicago Convention). This convention had set down rules for civil aviation, to work with states and industry to reach consensus on civil aviation standards, recommend shared practices and to limit the military mobilisation of air forces (269)

In Europe, discussions on the integration of agricultural policy began immediately after the Second World War had ended, though a policy did not appear until the 1960s. The European Coal and Steel Community, first proposed by French foreign minister Robert Schuman on 9 May 1950 as a way to make further war between France and Germany "not merely unthinkable but materially impossible" (270) ,was formally established in 1951; the European Atomic Energy Community (EURATOM) followed in 1958 to form a common market for the development of the peaceful uses of atomic energy, and a focus on the integration and interconnection of European electricity systems intensified with the work of the Committee of European Economic Co-operation and the *International Power Programme.* Coordination around European road construction and integration was enacted by the Inland Transport Committee (ITC), a unique intergovernmental forum of the United Nations Economic Commission for Europe set up in 1947 (54). All of these European reconstruction activities to build the peace were underpinned by Marshall plan aid and assistance from the USA.

4.2.3 Summary: Second World War

Perhaps the most profound imprint that was left by the shared sacrifice endured by so many during the Second World War was a yearning for peace and freedom. Indeed, individual freedom was the rallying call in a new and more global world (90). The era of mass consumption and abundance had arrived, underpinned by pipelines, refineries, runways, aircraft, centralised electricity grids, and intensified agriculture. However, the stability of this new era was predicated on the simultaneous centralisation of regulations and institutions coordinating sociotechnical systems at the national level and the increasing internationalisation of sociotechnical systems, trends that had in part been intensified in response to the unprecedented problems and logistical challenges of total war. As optimism grew for a new peace however, sociotechnical systems also continued to be entwined with military and defence imperatives under the 'permanent mobilisation' of the Cold War.

4.3. World War One & Two and the consolidation of Meta-rules.

In this section we discuss what rules and meta-rules can be identified from the analysis of the influence of mechanisms of total war and imprints of war on energy, food and transport. We do not claim that these rules were created by the wars. Rather they can be considered as inflections of modernity that were amplified and intensified through total war. There will likely be many other potential candidates for potential rules however the rules we now discuss are those that have emerged from the interpretive analysis above. In the aftermath of the Second World War, these rules manifest in all three sociotechnical systems and can therefore be considered meta-rules.

The Imperative of achieving abundance and constant supply

It was during the First World War that the importance of oil and challenges around securing its supply was fully recognised as a strategic problem on which state power depended, imprinting on post-war policy decisions and geopolitical strategy; challenges around sustaining supplies of electricity, producing sufficient amounts of food, and solving transport logistics were decisive factors in whether war would be won or lost. As the size and intensity of the war machine that the sociotechnical systems of energy, food and transport had to provide for reached an even greater scale in the Second World War, the pressures to overproduce and maintain a consistent delivery of oil, electricity, food rations, or transport flows, increased markedly. Mass pipeline construction, intensification in agricultural production and acceleration in use of new food preservation and

transportation techniques, as well as mass production of aircraft and expansion of infrastructural and logistical capabilities to ensure continual flow of aircraft, were all rapidly developed as a result of war. This system of abundance and constant supply was reconverted to civilian ends after the Second World War and systems now oriented around problems of abundance rather than scarcity in North America emerged. Europe was dominated by a condition of tragic scarcity after the Second World War, yet abundance and constancy of supply became a driving imperative in the rebuilding of Europe.

Centralise

The second proposed meta-rule is the imperative to centralise. Again, it seems that the First World War played a crucial role in aligning sociotechnical systems towards the tendency to centralise in response to particular demand pressures and logistical challenges This applies with regards to technical, institutional and regulatory domains. For example, both in terms of engineering solutions oriented around interconnection and new centrally coordinated management, electricity production was centralised during the First World War (81,128); New state institutions coordinated oil supply and food supply; nationalisation took place in some cases such as the railroads in the USA and the coal industry in the UK; the 'anarchy' of the automobile was 'tamed' through centralised approaches to traffic management and road construction. This meta-rule was imprinted in the post First World War environment however decayed through the 1920s. Centralisation became re-amplified as states once-again intervened more forcefully in response to the great depression and then mobilisation for the Second World War. The meta-rule of centralisation intensified to unprecedented levels during the Second World War seen, for example, in the re-application of centralised approaches to electricity grid management and specialised government roles to direct specific industries such as oil. This meta-rule of centralisation imprinted strongly in the 'golden age' with increasingly large farm sizes, state-controlled energy systems, centralised electricity grids, large national R&D science programmes coordinated by new state organisations, and mass state investment in road infrastructure. Ultimately, the wars had influenced the emergence of increasingly autarkic and technologically-advanced nation states (135), predicated on centralised bureaucracies that at the time, appeared to have a new mastery to control and mobilise sociotechnical systems.

Coordinate Internationally

The centralisation processes were only one part of the dual move initiated by war. Some countries were more tightly integrated as a result of war. It seems counter-intuitive at first, given that the most obvious consequence of war in terms of geopolitics is to create divisions between nations. Yet, to meet the challenges of maintaining the delivery of sociotechnical systems for the functions of war, certain countries were brought closer together in order to deal with various logistical challenges (271). The First World War intensified the meta-rule to coordinate internationally. This can be seen with First World War developments including the Inter-Allied petroleum conference for oil and recognition of the importance of international coordination for an emergent air industry. Post-war policies and building the peace influenced internationalism to stabilise the management of sociotechnical systems. With the emergence of the League of Nations food supply group, discussions and platforms of integrating road traffic systems in Europe in the 1920s, and the Achnacarry agreement with respect to oil, this meta-rule persisted however dissipated in many areas by the 1930s. This meta-rule intensified once again with Inter-Allied coordination in the Second World War. This can be seen with the coordination of oil supply in the Second World War, the international exchanges of science and expertise essential for the Manhattan project, and allied coordination to manage and coordinate the high volumes of air traffic for the war effort. Both with regards to maintaining the peace and managing abundance, international solutions were required after the war.

synergise with defence imperatives

After the First World War, military influence lingered in all three sociotechnical systems despite conditions of total war no longer officially being in place. For example the Highway Act in 1921 in the USA was directly related to military concerns about logistical bottlenecks, the strategic alliances forming after the First World War in relation to oil related to an oil frenzy sparked by recognition of the national security significance of oil. The military

importance of self-sufficiency in food supply was also a clear lesson from the First World War experience. After the Second World War the same trend became even more pronounced with developments in nuclear energy, interventions for oil supply, mass R&D investments in aircraft industry, and the expansion of use of DDT all being influenced by their continued military significance as part of a new cold war 'military-industrial-complex' (267). Rather than a shaper in exceptional times and confined to wartime, the growth of military power and 'warfare states' (40) left imprints that continued to profoundly influence sociotechnical systems. Particular strategic decisions that shaped the directionality of sociotechnical systems after both wars were often guided by which particular direction would benefit military-related priorities. Thus, this meta-rule is one where activities and decisions related to sociotechnical developments are shaped by how they are connected or may be of benefit to military aims.

To summarise, it seems that during world wars certain rules intensify and are amplified by the specific environmental conditions of total war. These coordinate as meta-rules, being present in all three socio-technical systems. Drawing on the imprinting concept these meta-rules continued into peacetime after the First World War however experienced decay. However, with mobilisation for the Second World War and the subsequent conflict, these meta-rules were re-amplified once conditions of total war were once again established. Following the resumption of conflict, these meta-rules persisted and became crucial to the stabilisation of the post-world war two era of mass consumption. Although these rules and meta-rules should at this stage be considered propositional, a provisional conclusion regarding the role of wars in the first Deep Transition can be made as follows: the Role of the world wars in the culmination of the first deep transition is the intensification and stabilisation of meta-rules across sociotechnical systems.

5. Discussion and Conclusion

Our interpretive analysis has outlined how solving the unprecedented challenges of wartime influenced the energy, food, and transport systems creating new opportunities for certain technologies (such as oil or the automobile) while significantly destabilising or revealing weaknesses in other areas (such as coal, rail, or traditional farming methods). New policy capacities including increased state intervention, and the creation of new institutions to manage sociotechnical systems coalesced to form solutions to the unprecedented challenges of total war. New policy capacities were formed internationally with collaboration across borders to manage the delivery of what had become the shared over-arching function of each sociotechnical system: winning the war. Competition between different actors within sociotechnical systems were at times suspended and new forms of cooperation were developed around a sense of shared sacrifice and cooperation. These wartime mechanisms played a key role in enabling the integration of disparate electricity systems and the emergence particularly in North America of a surplus of pipelines, airplanes, runways, and intensified agricultural systems.

We then discussed how the experiences of war imprinted on these systems in various ways, with the varied conditions of abundance in North America and scarcity in continental Europe manifesting after each conflict. Roads were constructed specifically related to military demands; institutions created in wartime continued in peacetime around key strategic resources such as oil; self-sufficiency in increasingly intensive agricultural production was pursued owing to wartime experiences of scarcity. While the partial decay of these imprints occurred with the return of market competition in the 1920s, these imprints were re-amplified in the build up to the Second World War and intensified during the conflict. The "tentacles of war" stretched into every nook and cranny of sociotechnical systems during the Second World War, however this time they did not retract but persisted in guiding the characteristics and the direction of travel of energy, food, and transport as meta-rules coordinating sociotechnical systems in a similar direction.

In carrying out this analysis, this paper has contributed to a more material account of how the institutional changes observed in the Techno Economic Paradigms (TEP) approach and other accounts of wartime

transformation are influenced by the particular problems and challenges facing sociotechnical systems and their reorientation to deliver a wartime function. The DT framework posits that rules that underpin great surges of development originate in sociotechnical systems which become aligned across systems as meta-rules coordinating sociotechnical systems in the same direction. While we refrain from discussing the origins of the rules that we have identified, we outlined how achieving abundance and constancy of supply, centralisation, internationalisation, and a tendency towards synergising with military and defence imperatives intensified during both world wars and persisted in the post-Second World War era across the transatlantic zone.

Pertinent to the DT framework, Pickering (19, p.5) refers to the emergence of the "world war two regime" where "pre-war boundaries between science and the military were breached" and where transformations in science and the military "…were sustained by those breaches and flows". It could be posited that the same breaching process was evident across the three sociotechnical systems of energy, food, and transport, where through the intensified and amplified meta-rules that persisted after World War II, the "World War Two Regime" continued to develop and mutate across sociotechnical systems in the enduring permanent mobilisation of the Cold War. This regime constitutes a 'rule set' that was amplified and persisted as a result of total war.

Returning to the overarching framework of Deep Transitions, a value of the imprinting concept is that it enables an understanding of how 'macro-events' can have enduring effects on sociotechnical systems. The way in which imprints endure is that rules and meta-rules amplified during wartime become embedded in sociotechnical systems. What can be considered as the paradox of total war, sees an 'external' landscape event for a brief and limited time period, engulfing both the regime and niche levels of the MLP driving and indeed enforcing disruptive and redirected system change. Overtime, this engulfment recedes in peacetime to a more normal background condition. Intensified meta-rules, amplified by wartime, can however continue to influence sociotechnical systems even though the story of their intensification by war may long be forgotten. Another point requires further elaboration in relation to the DT perspective however. This is the question of how imprinting functions in relation not just to sociotechnical systems but also the landscape category of the MLP. In onward work on the development of the food system and chemical weapons, we explore how imprinting can also have influence in changing the landscape in terms of broader symbolic shared memories and expectations that result from the experiences of total war.

Beyond the DT framework, a broader point with regards to sustainability transitions is how issues of warfare and the military can be accommodated in future research. Indeed, whether it is the development of the aeroplane as a military rather than civil technology (65),or the links between developments in food and agriculture systems with chemical weapons, the continual ties between oil exploitation and military power (170,272) and the ongoing imprints of defence-related nuclear activities on civil nuclear power trajectories (273–277) a more dynamic interplay between war and the military and sociotechnical systems seems to be at play that warrants closer attention. The implications for this are significant, as it draws attention to the need to problematise and probe the neat categories often assumed in transitions research between different 'sectors' or 'regimes' (278), and more generally of a "…division, implicit but powerful, between things which belong to the realm of the military and those in the world of science and technology that are taken to be essentially civilian" (279, p.138).

It is worth briefly considering the contemporary implications of this research in terms of emergence of a second deep transition and transformation agendas more generally (1,3). With regards to issues such as rapid climate change mitigation for example, calls are increasingly being made by some climate activists, NGOs, economists, and politicians, for a "mass mobilisation" similar to the industrial feats achieved in the United States during the Second World War (48,97,280). In other words, mass mobilisation for a 'war against climate change'. We caution against this approach however. Whilst mechanisms of war are useful in thinking about particular mobilising forces, the dangers of securitisation discourse and the unsustainability and horror of war emphasises the need to examine mobilising forces that are not reliant on war and 'external enemies' but rather are centred on the promotion of peace. Future research could therefore examine how different landscape dynamics outside of war and military influence can assist in understanding the diversity of mobilising forces.

We argue that the evidence put forward in this paper regarding the central role of the world wars in influencing the development of sociotechnical systems, are relevant to thinking through questions of why transformations to sustainability are not occurring at the speed and depth deemed necessary. Indeed, the enduring influence of imprints of war that we have emphasised in this paper, highlights just how implicated systems of mass violence have been in accelerating and shaping the development of centralised sociotechnical systems with an insatiable appetite for fossil fuels that have contributed to the production of numerous and enduring environmentally destructive processes.

In short, the synergistic relations between military systems and sociotechnical systems for food, energy, and transport that emerged through the course of the two world wars and sustained as the 'Military Industrial Complex', were central components of the acceleration to a condition of *unsustainability*. Sustainability transitions research and ongoing policy discussions on climate change mitigation and other challenges, could consider more centrally in their analysis and ongoing scenario work, difficult questions around what the role of war and the vast energy intensive and fossil-fuel dependent war machines that have evolved since World War II will be in future sustainability trajectories. It could even be questioned whether the enduring commitments to military systems and the massive R&D expenditures accompanying these commitments are compatible with ambitious goals around rapid emissions reductions and the like. Considering such questions and foregrounding the promotion of peace as a key component of sustainability, is arguably a more useful endeavour for sustainability research than joining the worrying contemporary embrace of war rhetoric.

Acknowledgements

This work was supported by James Anderson and Baillie Gifford & Co. We are very grateful to our Deep Transitions colleagues Johan Schot, Ed Steinmueller, Laur Kanger, Bipashyee Gosh, Frederique Bone, Daniele Rotolo, Florian Kern, Helen Sharp, and Geraldine Bloomfield for their useful feedback and assistance as this research has progressed. We also give thanks to all those that attended our workshop on Deep Transitions and War in June 2018. Thanks to Jon Agar and David Edgerton for useful discussions on this topic. This work has benefited from many conversations with colleagues at the Science policy Research Unit (SPRU), University of Sussex, including Tim Foxon, Andy Stirling, Sabine Hielscher, Rob Byrne, Marie Claire Brisbois, Divya Scharma, Matthew Lockwood, Paul Kivimaa, Adrian Ely, Adrian Smith, Barbara van Dyck, and Matias Ramirez. Thanks to Jonas Torrens now at the University of Utrecht for some very useful discussions and for introducing Phil to 'systematic combining' methods. Thanks also to those that attended a discussion and gave useful feedback when we presented a version of this paper at the IST 2019 conference in Ottawa. We are also grateful to Michael Hopkins at SPRU, and Brianne McGonigle at the University of Utrecht who both commented on earlier drafts of this paper. We thank the two reviewers of this working paper and the SWPS editors, whose comments contributed to substantially improving its content. All remaining flaws of course remain our own.

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Suggested citation:
Phil Johnstone and Caitriona McLeish (2020). The Role of War in Deep Transitions: Exploring Mechanisms, Imprints and Rules in Sociotechnical Systems. SPRU Working Paper Series (SWPS), 2020-04: 1-40. ISSN 2057-6668. Available at: www.sussex.ac.uk/spru/swps2020-04

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