World Wars and the age of oil: exploring directionality in deep energy transitions

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Abstract

This paper explores the role of the world wars in 20th century energy transitions focussed on the growth of oil as a major energy source which accelerated after the Second World War in North America and Europe. We utilise the recently developed Deep Transitions framework which integrates Techno-Economic Paradigms (TEP) and sociotechnical transitions approaches. The first deep transition entails the long running emergence of industrial modernity since the late 18th century that culminated in the post-Second World War economic ‘golden age’ underpinned by rapid and stable growth and prosperity in North America and Western Europe. The Deep Transitions framework draws attention to the increasing role of fossil fuels over this long time period, which accelerated in the 20th century and took on a particular direction as multiple sociotechnical systems including energy, mobility, and food became increasingly reliant on oil while the share of coal as a proportion of the overall energy mix, decreased. This paper focusses on the wartime experiences of the USA and the UK and focusses on the specific demand pressures and logistical challenges experienced in wartime in multiple sociotechnical systems and how the search for new solutions to these problems shaped the development of the age of oil.

1. Introduction

The post-World War II era saw the share of oil in energy consumption rapidly increase where abundant supplies of oil and petroleum products were seen as key in underpinning the so-called “golden age” of economic development. This period constitutes a sustained period of high economic growth, prosperity, and the rise of mass consumption in North America and Europe lasting until the oil crisis of 1973. While the importance of the post-World War II era is often emphasised in energy transitions research, until recently, as Evenden [1] points out, there has traditionally been a smaller proportion of studies focussed on how wartime activities influenced these developments. In recent years however, there is a growing sub-set of literature that has focussed on the importance of world war as a factor in energy transitions [1–4]. And in history and geopolitics, oil resource geographies, developments in oil technologies, uses, industry, infrastructures, logistics, and patterns of import and export during wartime have been detailed [5–9]. This paper contributes to emerging literatures on war and energy transitions [10–12], integrating insights from historical and geopolitical literatures with sociotechnical perspectives to understand the role of world war in the 20th century development of the “age of oil” [13].

In doing so, this paper builds on the ‘Deep Transitions framework’ (here on in “DT”) introduced by Schot and Kanger [14]. The DT framework is new and constituted by numerous concepts which we discuss in more detail in section 2.2. To summarise however, while the DT framework was proposed the framework combines the Techno Economic Paradigms (TEP) approach developed by Carlota Perez [13], and sociotechnical transitions theories that drawing on the Multi-Level Perspective (MLP) [15].
Both the TEP approach [16,17] and the MLP [18,19] have been frequently drawn upon to understand energy transitions.

The TEP approach builds on long wave theory widely used in economics for several decades [20], and identifies different phases of economic development (what are referred to as ‘great surges’ of development). These are depicted as occurring over 40-60-year periods, and are driven by the unleashing of particular technological innovations (such as the internal combustion engine), a paradigm of economic growth that coordinates activity (such as ‘mass production’), particular forms of financial investment, and a source of cheap energy which underpins a particular ‘surge’ of economic growth. For the purposes of this study, the most relevant point to note is that TEP framework specifically names the period from 1908-1971 as “the age of oil, the automobile, and mass production” where “the cheapening of oil-based fuels, electricity and road transport gave positive support to the very high growth rates of national mass markets” ([13]: 136). The TEP framework has generally focussed at the ‘macro’ level of analysis entailing broad changes in entire economies driven by technological innovation and cycles of financial investment.

Analysis drawing on the MLP on the other hand, has focussed at the level of ‘sociotechnical systems’ entailing different systems for providing societal needs, such as energy or mobility. Different elements including technology & science, markets & users, industry, institutions & regulations shape activities within a sociotechnical system. MLP approaches tend to focus on how new technologies and practices operating in protective spaces of novelty called “niches” can come to destabilise dominant sociotechnical regimes, which represent the dominant technologies and institutional configurations through which a particular societal need is delivered. Rather than the ‘macro’ approach of TEP, the MLP’s focus on individual sociotechnical systems is understood as a ‘meso’ level approach. The framework has been used to examine the co-evolutionary dynamics of important historical technological change such as the transition from sailing ships to steam ships [15], as well as historical analysis focussed on the long-term decline of previously dominant technologies such as the case of the UK coal industry in the 20th century [21].

However, while world wars are mentioned as relevant exogenous factors ‘in both TEP and MLP literatures, activities during world war and the sociotechnical implications of wartime have generally not been a focal point of analysis. The DT framework addresses this gap, with one of its key propositions (proposition 7) being that ‘external shocks’ and particularly world wars, are decisive ‘turning points’ in coordinating multiple sociotechnical systems (energy, food, and mobility) in a similar direction.

The notion of ‘directionality’ is central to the DT framework. Building on the work of Stirling [22], Schot & Kanger outline their understanding of the term as follows: “socio-technical change has a direction, choices are made between directions and actors gradually become blind to alternatives, which is a central tenet of much of the innovation studies literature” ([14]: 1045). Thus, a focus on ‘directionality’ recognises the plurality and diversity of potential energy transitions and is attentive to historically contingent factors whereby certain energy trajectories become dominant and alternatives are ‘closed down’ as technological market structures, regulations, political support, infrastructure, user practices, align to form a particular technological trajectory that gains momentum and makes it challenging for new technologies and practices to break through [22].

To take one example, electricity grids designed around the production of constant ‘baseload’ production utilising increasingly large power plants made it very challenging for variable renewables and energy demand measures to break through in many countries without concerted political pressure over several decades [23]. Energy transitions therefore usually take several decades and are
fraught with political struggles, resistance by existing energy incumbents, and usually require governmental intervention to overcome these barriers.

A key aspect of the DT framework is that in understanding sociotechnical directionality, the focus is on the co-evolution and alignment of multiple sociotechnical systems, where the tendency in sociotechnical approaches has been to focus on single systems [24]. Direction is further refined in the DT framework through the concept of rules, which is a well-established concept used in institutional studies and a core concept of the MLP. Schot and Kanger define rules as “humanly devised constraints that structure human action, leading to regular patterns of practice” ([14]: 1053). An example of rules given by Schot and Kanger is an “imperative to use fossil fuels”. After the Second World War this rule became dominant in energy, food, and mobility and therefore constitutes a ‘meta-rule’. This is because the rule structures human action and influences regular patterns of practice in multiple sociotechnical systems (energy, food, mobility), rather than single systems.

Another “meta-rule” identified that becomes particularly amplified in the conditions of the First and Second World War is the ‘imperative to maintain abundance and constancy of supply’ [25]. Numerous historians have pointed out that after the Second World War an era of ‘energy abundance’ based on cheap oil emerged in the USA [26–28], and then in many European countries as “the years of surplus” from 1955 onwards [29]. The expansion of oil and a system of energy abundance are closely linked [26]. In this paper we explore the emergence of “the age of oil” identified by Perez which forms the final stage in the emergence of the first deep transition. We combine geopolitical and historical literatures with a sociotechnical approach to understand how the heightened conditions of maintaining abundant and constant supply during the First and Second World War influenced this particular direction in energy transitions in the twentieth century. Given our focus is on the final stage of the first deep transition which Schot and Kanger recognise is characterised by a shift to oil in multiple sociotechnical systems, we are focussed on how the rule entailing an imperative to use oil was influenced by wartime events. The overall research question is as follows: what was the role of world wars in shaping the emergence of the age of oil in the culmination of the first deep transition?

Building on diverse literatures from geopolitics and history, it is possible to build a plausible and evidence-based narrative to answer this question. In undertaking this analysis, there are two central aims. The First is to make a contribution to the emerging literature on energy transitions and the role of world war. Secondly, we respond to the proposition 7 of the Deep Transitions framework, concerning the key role of war in the coordination and alignment of sociotechnical systems.

We proceed as follows: section 2 situates this paper in the wider context of the broad field of ‘energy transitions’ research, and specifically the emerging interest in wars and the military as key factors in energy transitions. We then further elaborate the DT perspective, explaining key concepts and how discussions of deep transitions align with and can contribute to energy transitions literatures. In section 3, after discussing our approach, we outline an interpretive analysis drawing on extant literatures from history and geopolitics to build an interpretive evidence-based account of the role of the world wars focussing on World War I, the inter-war years, World War II, and the post-war period of re-orientation and reconstruction.

The focus on the USA and UK is motivated by first, the fact that core to Perez’s theorisation of the age of “oil and mass production” is the lead role played by the USA and how oil-dependent forms of economic activity ‘diffused’ to Europe; second, the central role relations between the USA and the UK play – both as a point of friction and collaboration – in historic accounts of oil developments and geopolitical struggle [7,30]. Given the nature of war and geopolitics, understanding the strategies of these two countries around oil necessarily involves reference to the oil strategies of other belligerents.
What is more, the focus of this analysis is not to diminish the importance of oil developments in other countries. However, the focus on these two countries provides a necessary boundary (given the breadth of this topic) to focus on the sociotechnical responses during war, and also international dynamics of friction and collaboration in US and UK oil relations identified as a significant factor in historical studies [7]. While firm conclusions cannot be reached without further analysis, there is considerable historic literature on the post-war reconstruction and reconversion period in Europe that has implications for understanding potential drivers of rapid oil transitions in Europe more generally.

In terms of the overall contribution of this paper, it is worth highlighting that the authors are aware of the geographical limitations of the present study. Our focus is on breadth rather than depth (covering a time period entailing two world wars), and so there will necessarily be gaps in the analysis. Entire sub-fields of historical analysis are devoted to just one war, or even a war in a particular country. However, we seek to contribute to opening up for further elaboration and testing, propositions that can contribute to emerging discussions around energy transitions and world war, through answering the question of the role of world war in influencing the directionality of the first deep transition. While history is not a guide to the future, we argue that the historical imagination [31], can contribute to enriched discussions in energy transitions on possible drivers and mobilising forces for sustainable energy transitions.

2. Situating this study within “Energy transitions” research: world war and deep transitions

We now situate the present study in the wider field of energy transitions research, and then go on to discuss the DT framework, and our approach.

2.1 Energy transitions research and world war

‘Energy transitions’ is a broad and multi-disciplinary area of study. There are multiple definitions and interpretations. In a discussion of the ‘emerging field of energy transitions’, Araujo outlines a broad definition of the term: “a shift in the nature or pattern of how energy is utilized within a system” where “an energy system is a constellation of energy inputs and outputs, involving suppliers, distributors, and end users along with institutions of regulation, conversion and trade”(32) ** P.112. Araujo continues that “change can occur at any level – from local systems to the global one – and is relevant for societal practices and preferences, infrastructure, as well as oversight” (32) ** p.112. While some authors try for more precision in defining energy transitions1, Sovacool concludes that “there is no standard or commonly accepted definition of an energy transition in the recent academic literature” (12) ** p.205, but rather, there are different foci of analysis and conceptual tools which form the basis for differing perspectives.

Thus, rather than attempting to establish a strict definition, the key question is what perspectives are being used as an entry point to understanding energy transition phenomena and what particular

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1 For example, Smil outlines that an energy transition is the time that elapsed between the introduction of a new fuel and its rise to a 25% national or global market share, or Grubler, outlining ‘grand transitions’ as a new fuel reaching 50% market share. Yet, these are not rigid definitions that should be adhered to, but one amongst a plethora of perspectives that constitute and varied and interdisciplinary broad field of research [12].
discussions in energy transitions does the present analysis relate to. First, this paper relates to ongoing discussions on ‘historic energy transitions’ as Fouquet identifies [10], which has seen more detailed examination of the historic factors influencing the speed and dynamics of transitions from the level of a single fuel or technology to the global scale [10,33,34]. Sovacool & Geels highlight that interpretations of historic transitions vary widely because there are different points of focal interest in terms of the ‘multiple dimensions’ of energy transitions [35]. This can include techno-economic analysis which focuses more on firms, sunk costs, investments, and the difficulties and long-time frame that energy transitions entail because of these economic factors, and ‘socio-institutional analysis’ which focus on political and policy interventions that influence past transitions and can ‘trump’ these economic constraints.

A perspective that tries to bridge these ‘multiple dimensions’ and that Sovacool and Geels identify as “a key conceptual approach” in energy studies is ‘sociotechnical transitions’ approaches [35]. This perspective focuses on the co-evolutionary changes in energy systems that entails a focus on elements including technology & science, markets & users, industry, institutions & regulations, where these different elements interact to form a ‘seamless web’ to deliver a particular societal function [36]. As Sovacool points out, many studies that take a sociotechnical perspective draw on the MLP which examines interactive developments between sociotechnical niches, regimes, and landscape pressures. A sociotechnical regime represents the dominant way of doing things, in terms incumbent technologies and the rules and institutions that guide developments in an energy system. Niches, on the other hand, represent the level of novelty, innovation and experimentation [37].

However, despite a plethora of work drawing on a sociotechnical perspective and the MLP, the ‘landscape’ level often remains underexamined in such accounts. This includes wars, which in historic accounts drawing on the MLP are often used as temporal markers depicting discontinuity between different stages of development in energy transitions [21], rather than focal points of analysis.

However, recently energy transitions scholars have focused more on world wars as a factor in energy transitions. For example, Samaras et al [38], in detailing the contemporary role of the US military in energy R&D around insulation, and mini-grids, and also highlight how strategic military decisions have shaped energy developments discussing the First World War transition of the British naval fleet to oil [39]. Evenden has conducted detailed analysis of the ways in which the Second World War mobilisation efforts in Canada played a decisive role in accelerating transitions to hydroelectric power under emergency measures to maintain adequate electricity supply to fuel industrial efforts for World War II [1,4,40]. More recently, Cohn, Evenden, & Landry, conducted a historical analysis of Canadian, German and American mobilisation during the Second World War, and how it played a crucial role in influencing the design of electricity systems in these countries [41].

Of particular relevance to this paper, recent work by Ediger & Bowlus [3] move beyond commercial and technological factors conducting an historical analyses of the importance of oil for military strategy in the build to and during the First World War, highlighting the central role of geopolitics in energy transitions. Rubio-Varas also focuses on the First World War, highlighting how disruptions caused by the conflict were decisive in influencing a rapid transition to oil that occurred in Latin America, decades before Europe [2]. The present work builds on and seeks to contribute to this sub-field, through engaging with the DT framework which we now discuss.
2.2 The Deep Transitions framework (DT), energy and war

In this section, we discuss the DT framework, its constituent conceptual elements, what it is attempting to achieve and how it can be utilised to explore energy transitions. The framework builds an understanding of long-running developments in multiple sociotechnical systems across a 250-year period from the late 18th century culminating in the post-war ‘golden age’ of economic growth and prosperity [14, 42]. The first deep transition is theorised as entailing four different ‘great surges’ of development across this time period which constitute the slow building up of industrial modernity. The focus of the present work is on the ‘fourth surge’ which for Schot & Kanger represents the culmination of the first deep transition (fig. 1). The red circle in figure 1 highlights the fourth surge. Each surge constitutes a “technological revolution” entailing a period of economic growth, based around a “…constellation of new inputs, products and industries, one or more new infrastructures – usually involving novel means of transport of goods, people and information– and alternative sources of energy or ways of getting access to it” (43) ** p.4. The details of each surge are outlined in figure 2.

Figure 1: The first and second deep transition. Source: Schot & Kanger [44]
For Perez, each surge follows a pattern of irruption, where a number of new technological innovations emerge, a period of ‘frenzy’ where there is a battle between old and new technological configurations and economic paradigms, a period of “synergy” where there is resolution and a particular new economic paradigm becomes stabilised, and then a period of “maturity” where the particular paradigm and its constituent technologies and economic paradigms reaches saturation point, ending in crisis with the absence of new growth opportunities. These stages are outlined in figure 3:

### Figure 2: great surges of development. Source: Perez [43]

For Perez, each surge follows a pattern of irruption, where a number of new technological innovations emerge, a period of ‘frenzy’ where there is a battle between old and new technological configurations and economic paradigms, a period of “synergy” where there is resolution and a particular new economic paradigm becomes stabilised, and then a period of “maturity” where the particular paradigm and its constituent technologies and economic paradigms reaches saturation point, ending in crisis with the absence of new growth opportunities. These stages are outlined in figure 3:

<table>
<thead>
<tr>
<th>Technological Revolution</th>
<th>New technologies and new or redefined infrastructures</th>
<th>New or redefined infrastructures</th>
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<tr>
<td>FIRST: From 1771&lt;br&gt;The Industrial Revolution&lt;br&gt;Britain</td>
<td>Mechanized cotton industry&lt;br&gt;Wrought iron&lt;br&gt;Machinery</td>
<td>Canals and waterways&lt;br&gt;Turnpike roads&lt;br&gt;Water power (highly improved water wheels)</td>
</tr>
<tr>
<td>SECOND: From 1829&lt;br&gt;Age of Steam and Railways&lt;br&gt;In Britain and spreading to Continent and USA</td>
<td>Steam engines and machinery (made of iron; fuelled by coal)&lt;br&gt;Iron and coal mining (now playing a central role in growth?)&lt;br&gt;Railway construction&lt;br&gt;Rolling stock production&lt;br&gt;Steam power for many industries (including textiles)</td>
<td>Railways (Use of steam engine)&lt;br&gt;Telegraph (mainly nationally along railway lines)&lt;br&gt;Great ports, great docks and worldwide sailing ports&lt;br&gt;City gas</td>
</tr>
<tr>
<td>THIRD: From 1870&lt;br&gt;Age of Steel, Electricity and Heavy Engineering&lt;br&gt;USA and Germany overtaking Britain</td>
<td>Cheap steel (especially Bessemer)&lt;br&gt;Full development of steam engine for steel ships&lt;br&gt;Heavy chemistry and civil engineering&lt;br&gt;Electrical equipment industry&lt;br&gt;Copper and cables&lt;br&gt;Canned and bottled food&lt;br&gt;Paper and packaging</td>
<td>Worldwide shipping in rapid steel steamships (use of Coal Canal)&lt;br&gt;Worldwide railways (use of cheap steel rails and bolts in standard sizes)&lt;br&gt;Great bridges and tunnels&lt;br&gt;Worldwide Telegraph&lt;br&gt;Telephone (mainly nationally)&lt;br&gt;Electrical networks (for illumination and industrial use)</td>
</tr>
<tr>
<td>FOURTH: From 1908&lt;br&gt;Age of Oil, the Automobile and Mass Production&lt;br&gt;In USA and spreading to Europe</td>
<td>Mass-produced automobiles&lt;br&gt;Cheap oil and oil fields&lt;br&gt;Petrochemicals (synthetic)&lt;br&gt;Internal combustion engine for automobiles, transport, tractors, airplanes, war tanks and electricity&lt;br&gt;Home electrical appliances&lt;br&gt;Radio and Television&lt;br&gt;Refrigerated and frozen foods</td>
<td>Networks of roads, highways, ports and airports&lt;br&gt;Networks of all ducts&lt;br&gt;Universal electricity (industry and homes)&lt;br&gt;Worldwide analog telecommunications (telephone, telegraph and cablegram) wire and wireless&lt;br&gt;National broadcast networks</td>
</tr>
<tr>
<td>FIFTH: From 1971&lt;br&gt;Age of Information and Telecommunications&lt;br&gt;In USA, spreading to Europe and Asia</td>
<td>The information revolution;&lt;br&gt;Cheap microelectronics;&lt;br&gt;Computers, software&lt;br&gt;Telecommunications&lt;br&gt;Control instruments&lt;br&gt;Computer-aided biotechnology and new materials</td>
<td>Worldwide digital communications (cable, fibre optics, radio and satellite)&lt;br&gt;Internet/Electronic mail and other e-services&lt;br&gt;Multiple source, flexible use, electricity networks&lt;br&gt;High-speed physical transport links (by land, air and water)&lt;br&gt;Global nanowiring networks</td>
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Figure 3: stages of a great surge. Source: Perez [43]

Although building on the ‘great surges’ approach, the DT framework differs in several important ways. First, the framework emphasises continuity across these surges, where the first four surges represent a single deep transition. Second, while Perez identifies a fifth surge based around Information Communication Technologies with renewable energy as the key energy input, Schot & Kanger propose that instead this period represents the beginnings of a second deep transition. As they outline, “through gradual accumulation and coordination, niches may contribute to a fundamental overhaul of existing socio-technical systems, introduce a new set of sustainable and just directionalities...and thereby give rise to the Second Deep Transition”(42) ** p.8. In this paper however, we are focussed on the culmination of the first deep transition and more precisely, “the age of oil” as depicted in the fourth surge. We do not discuss the second deep transition.

Third, the DT perspective posits that the drivers underpinning the emergence of particular surges can be understood from the perspective of the changing dynamics within sociotechnical systems. Innovation in niches is driven by system builders responding to particular problems in delivering societal needs and the search for solutions and improvements. The concept of rules discussed in the introduction, is used to understand how routines and behavioural patterns within sociotechnical systems that influence path dependency and form sociotechnical regimes. Where the Deep Transitions framework departs from most MLP-based analysis however, is it focusses on multi-system interactions and co-evolution, and how systems become increasingly aligned in a similar direction over time. That alignment process takes place when the same rule exists in multiple systems, referred to as a ‘meta-rule’.

An important point to also note, recognised by Schot & Kanger and Perez, is that the time periods of surges strongly overlap. It is not the case that one surge disappears completely as another emerges. Because due to issues of sunk costs, and resistance, there is considerable cross-over between surges as the elements of each surge are reconfigured and compete against each other until there is a resolution at a ‘turning point’. With respect to the fourth surge and the energy question, this relates to understanding how oil gained a significantly larger share of energy consumption by the end of the Second World War, in the USA, UK and Europe more widely while the share of coal (the dominant energy source of the previous two surges) decreased [16].
This interrogates the role of war in shaping oil transitions and how the rules of using fossil fuels and maintaining abundance and constant supply influenced these transitions. We now briefly discuss the approach taken to build our interpretive analysis.

2.3 Approach to the present study

In conducting our interpretive analysis we seek to integrate geopolitical historical accounts of oil developments in the twentieth century with sociotechnical perspectives. We focus on four different stages to frame our analysis based around Carlota Perez’s depiction of the age of oil following the stages of irruption (covering the time period of the First World War), frenzy (the interwar years), synergy (that includes the Second World War), and maturity (post World War II). In doing so, we are attentive to historical literatures which outline the key differences between world wars and peacetime based on the conditions of total war [45–47], where, as Van Creveld writes, “war itself extended its tentacles deep to the rear, spreading from the trenches into the fields, the mines, and the factories” (34, p.164). During periods of total war, entire economies and societies (rather than just a dedicated military) are mobilised for the war effort [48]. Sociotechnical systems (including energy, food, mobility) become mobilised as part of a singleness of purpose of achieving wartime aims [49–51]. Multiple sociotechnical systems are reoriented from delivering civil societal functions to also supplying vast militaries.

We focus during wartime on what Obinger et al refer to as a key mechanism of total war. This relates to the immense demand-pressures are placed on the economy and logistical challenges are presented that can reorient patterns of production and consumption [52]. Building on the DT framework and the recognition of the key role of maintaining abundant and constant supply during world wars [25], we build on diverse literature to build an interpretive account of how these exceptional demand pressures of total war influenced dynamics in multiple sociotechnical systems and the relevance these changes had for oil transitions. As Rip and Kemp outline, world wars provided a particular ‘selection environment’ for particular innovations and developments to ‘break through’ [36] Thus we focus on examples of strategic openings afforded for oil as a ‘solution’ to a variety of demand side challenges as well as being attentive to evidence of potential destabilising forces with regards to other technological pathways [53].

Obinger and Petersen also draw attention to the importance of the demobilisation phase were soldiers and workers employed for war production have to be reintegrated back into civil economies [54]. This phase presents a particular economic challenge in warding off economic collapse once the demand-pull effects of war time cease. Also relevant in this phase is the legacies of war as a catalyst for change, where policies can continue into peacetime. Of particular relevance for our study which is focussed on the USA and UK, is the legacies of policy diffusion and transfer which can be achieved in conditions of total war due to alliances between different countries and the effects of post-war reconstruction.

These mechanisms of world war, provide a guide to shape our narrative analysis. In doing so the analysis is interpreted around the core rule identified by the DT framework of the imperative to use fossil fuels. Given our focus on the fourth surge and the recognition of the special importance of transitions from oil to coal by Schot & Kanger [14], for the purposes of our focus, we have refined this as the imperative to use oil. In integrating broad trends, geopolitical developments, and a focus on demand pressures in multiple systems, we respond to our overarching research question: what was...
the role of world wars in shaping the emergence of the age of oil in the culmination of the first deep transition?

3. World Wars and the age of oil

In this section we outline our interpretive narrative of developments in multiple sociotechnical systems in four distinct periods, following the “age of oil, automobile and mass production” identified by Perez. First, we look at events in the First World War in the UK and USA, identifying broad trends and geopolitical developments, before discussing illustrative examples of relevant developments related to energy, food, and mobility for considering oil transitions. We then discuss geopolitical factors related to USA-UK oil relations and sociotechnical developments in the ‘frenzy’ period between the wars. Third, we focus on the ‘turning point’ of the Second World War in the ‘synergy’ phase. In the fourth part of our analysis, we look at the importance of post-war reconstruction efforts and the challenges of demobilisation. Drawing on literatures that are focussed on the influence of the Marshall plan on technological developments in Europe, we critically assess the extent to which America’s role shaped the wider diffusion of oil technology, infrastructures and governance relevant to the age of oil.

3.1 First World War and the ‘irruption’ of the ‘age of oil’

We now discuss the First World War and developments relevant to oil transitions. This section is shorter than the section on World War II because literatures in energy transitions research have already highlighted the importance of this conflict as significant in the emergence of oil transitions [3]. We extend this analysis through a focus on the multi-systemic demand-pull factors that influenced the enduring “thirst” for oil and related geopolitical developments [55]. We begin with a broad overview of broad trends and geopolitical developments before focussing on demand pressures and logistical challenges in energy, food, and mobility relevant to oil transitions.

3.1.1 Broad developments in energy and geopolitics in the First World War

Before the First World War the use of oil was limited with the main use being kerosene lighting [56]. In 1914 coal was still king. Oil provided under 5% of world energy supply while coal contributed to 74% [57]. In 1907, the value of the UK’s coal trade surpassed £52 billion while the total value of all petroleum exports from the USA amounted to some £19 million [57]. Yet the First World War was a significant rupture in this pattern of development as global use of petroleum grew by 50 percent [56]. In the century prior to the war, British geopolitical dominance was secured by its steam-powered navy, and at the turn of the 20th century, the UK was the world’s leading energy exporter [58] however the First World War interrupted this trend and concerns about access to oil would be key to these changing geopolitical dynamics [59].

The UK faced a central challenge during World War I as it had limited reserves of oil. During the war, 90% of the oil required for the British as well as French war effort was supplied by the USA [57]. The UK (along with France and Italy) became dependent on the USA to fuel this increasingly oil-intense conflict. These dynamics intensified with the oil crisis of 1917 where, due to the ever-increasing amounts of oil being consumed by militaries in Europe and the disruption of oil supply routes by
German submarine attack, there were significant risks of oil supply running out. Influenced by these intense pressures, the USA, UK, and other countries including France and Italy, were drawn closer together by the imperative to maintain constant supplies of oil. As Yergin points out, the oil crisis caused by the First World War was forcing the United States and its European Allies into tighter integration of supply activities [60]. Geopolitical tensions increased in the Middle East driven in part by the search for oil, with Britain attempting to gain control of important oil fields in Iraq. The Sykes-Picot Agreement signed in 1916 by the UK and France carving up Mesopotamia and is understood to have been partly influenced by desires to secure strategic oil resources [61,62] As several authors point out, the First World War and the thirst for oil amplified the geopolitical significance of the Middle East, leading to increased tensions between the USA and UK (along with France) after the war [3,9,63,64].

But these broad changes and geopolitical developments are rooted in specific sociotechnical challenges that the war environment presented. We now explore the demand pressures and logistical challenges caused by conditions of total war and the implications for oil transitions.

### 3.1.2 Demand pressures and sociotechnical developments in the First World War

In the years preceding the World War I, the advantages of oil ships had been recognised by many navies around the world. The advantages of oil over coal including that the fuel was double the thermal content meaning less space required for storage, logistics of refuelling at sea were made easier, reliance on docking stations for refuelling was reduced, there was greater flexibility in changing speeds, and less personnel required on ships [65]. Additionally, oil-based ships produced less smoke was beneficial to gunnery operations and provided more covert forms of naval activities [7]. An early mover to oil was the British Navy. The share of oil-based vessels in the British navy rose from 5% at the start of the war to over 40% by the war’s end [60]. Prior to World War I, most shipping was steam-powered, and thus the application of oil to navies was a key niche development supported by the military and accelerated by the First World War. During the conflict, the US navy which had already converted several ships from coal accelerated this trend [9]. Germany, on the other hand, did not use all-oil firing vessels until after the war [66].

Internal combustion engine-based automobiles and trucks were a niche in the mobility system before the war. However, they became increasingly used for tactical advantage during the war by the UK and USA as significant problems were experienced with rail road transportation. The First World War has been described as the pinnacle of the “rail age” [67], yet disruptions were experienced with bottlenecks on the Western Front in getting a constant supply of weaponry and materials to troops. In Allied campaigns such as the battle of Verdun, the rapid construction of roads and use of motor vehicles for transportation further entrenched the importance of oil for military victory [68]. An example used by historians to exemplify a general point about the greater military dependence on the automobile and trucks is that at the beginning of the war the UK military had 823 automobiles and 15 motorcycles. By the war’s end had 23, 000 motorcars, 63,000 trucks, and 34,000 motorcycles [9]. In the USA, railroad arteries were also blocked and under the auspices of the US High Transport Committee, caravans of trucks carrying important goods for the front line were initiated,

2 The decision had been made by Winston Churchill in 1911 to transition the entire British fleet from coal to oil and this is cited by historians to exemplify the general point concerning the greater dependence of militaries on oil emerging during World War I [9].
“inaugurating the long-distance trucking of freight as an alternative to rail transportation and calling attention to the great need for a national system of interconnected, improved highways” (69) ** p.78.

During the conflict, ‘air wars’ became a new reality. The airplane which was in its ‘embryonic phase’ as a niche technology at the start of the war had consolidated as a major industry by the war’s end increasing requirements for gasoline products [70]. In Britain, as Edgerton outlines, the created a very large aircraft industry, with increases in output accelerating through the war. Monthly output increased from about ten per month at the war’s beginning to 122 in 1917 and 2,688 in 1918. The number of people working in the aircraft industry in the UK rose from nearly 49,00 in October 1916 to 154,000 in November 1917 to 268,000 in October 1918 [71]. In the USA, there was also considerable airplane construction with 10,000 airplanes constructed by the war’s end [56], creating a surplus of aircraft after the war. As Heppenheimer writes, “the war had jump started our [The USA’s] aviation industry, as a flood of tax dollars brought a surge of new engines and aircraft.”[70].

Response to demand pressures in the food system also had implications for oil supply. Demands for food production greatly increased in the USA as exports to Allied nations expanded rapidly. Food imports became significantly disrupted and blockading food supplies became a key strategy of both the UK and Germany during this war. Thus, a focus on ‘self-sufficiency’ intensified in the UK [72]. There is evidence that the First World War also led to niche experimentation to maintain a agricultural supply in response to these demand pressures. Coal and steam power had not made significant inroads into the agricultural sector, however in the First World War strategic openings were revealed for the use of tractors. As Dewey notes, the war accelerated the development and marketing of traktors [73]. In the UK in 1917, the Government ordered 400 British Saunderson Tractors and $3.2 million was invested in US models such as the Fordson. Ford exported 7,000 tractors to Britain in an effort to boost agricultural productivity [74], and they remained utilised after the war. In the USA, tractor use also expanded under government loan schemes and propaganda campaigns and expos were used by government to further encourage their use [75].

3.2. The inter-war years, oil and geopolitical ‘frenzy’

We now discuss both broad developments and geopolitical developments as well as relevant sociotechnical developments with regards to the inter-war years.

3.2.1 Broad trends and geopolitical developments in the inter-war years

the First World War created an ‘oil frenzy’ which significantly influenced international relations after the war [57]. The 1920s can be considered as a period of international instability with respect to global oil supplies as the new recognition on the strategic importance of oil created tensions between different national oil interests. As Black notes, the First World War and the emergence of oil as a ‘strategic resource’[76] meant that “…new systems of negotiation and need had emerged that would eventually be referred to as “geopolitics.” (99) ** p.140.

Before the First World War, Britain controlled only 5% of the world’s oil production, but by the war’s end Britain had acquired 50% of the world’s known oil reserves [77]. France and the UK struggled for control over Middle Eastern oil resources, and in April 1920 the San Remo Agreement was reached.
Here, “Britain conceded a share of the oil in exchange for a general agreement, effectively granting France a 25 percent share of petroleum in exchange for Mosul” (118) ** p.41. This locked out foreign companies from being able to control oil production in the British Empire. The USA retaliated with similar measures, using the Mineral Leasing Act of 1920 to prevent any company from a nation that was excluding American oil companies in the Middle East from gaining access to US oil fields. New oil discoveries in Texas in 1924 eased this geopolitical tension. However, the new thirst for oil and wartime experiences of oil shortages had resulted in an ‘exploration boom’ [60,78]. This led to low prices which risked the stability of the global oil industry.

The “Red Line” Agreement at Achnacarry in 1928 sought to control global oil prices and form monopolies of control around oil access. The agreement saw the creation of the “Seven Sisters” oil cartel where the agreement was reached to cease the independent prospecting for oil in the Ottoman empire by individual oil companies, and instead conduct explorations in a coordinated manner as a cartel. This was an attempt to create stability in the global oil regime however tensions between the United Kingdom and the USA continued as Britain pursued a strategy of trying to secure its oil resource independently from America [59,60]. However, Britain did not have the industrial capacities to exploit significant amounts of oil in the Middle East, and the USA maintained its focus on exploiting indigenous oil reserves.

It is worth pointing out that the UK’s strategy for oil independence differed in the inter-war years from Germany in significant ways which would ultimately have implications for World War II. Germany was economically and politically weakened after the conflict and could not acquire oil reserves. A key part of the strategy was to pursue petroleum synthesized from coal [59]. Germany established a synthetic fuels industry to meet the rising demand for oil as the country continued to industrialise as the war preparation phase set in in the 1930s. The strategy of both countries had their limitations during this period of ‘frenzy’ however. The UK had put considerable effort into securing Middle Eastern oil supplies, and while in 1929 the USA produced more oil than any other country, British oil companies including Anglo-Persian and Anglo-Iranian oil produced more oil beyond the United States than every U.S company combined [59] with 41% of oil production outside of the US produced from British companies. However, this strategy proved flawed in the build up to the war as routes through the Mediterranean were hampered by Italy in the 1930s. Britain could not secure its supply routes and did not have adequate tanker capacity to transport the oil. The energy intensive process of producing synthetic oil from coal would also ensure that territorial expansion to acquire resources of crude oil would be key to German military planning and strategy in war [59].

3.2.2 Sociotechnical developments in the inter-war years

The imperative to maintain a constant supply of oil amplified by World War I had accelerated production in the US oil industry and this presented the challenge of re-orienting to peacetime activities. As Auzanneau writes “unable to settle down and smoothly adapt its production to the new conditions of peace, the oil industry experienced an intense overproduction crisis after 1918” (50) ** p.100. However, oil production and consumption continued to steadily increase in the USA, with the rise of car culture and mass consumption during the ‘roaring twenties’. However, in the UK this expanse was more modest. Despite being adversely effected by World War I and facing significant economic problems, rail was not challenged by road transportation to the same extent as in the USA in the “clash of cultures” between the automobile and rail systems in the inter-war years [80].
The significant wartime problems of bottlenecks in flows of truck freight resulting from poor road infrastructure experienced during the war gave impetus for mapping out and then funding improved road infrastructure in the USA. The Federal Highway Act 1921 to construct a joined-up road network linking US cities was unveiled specifically citing military considerations for better-maintained road infrastructure [81]. In the UK, the Ministry of Transport was established in 1919, introducing a national system of road signage, a system of grants for local authorities to construct roads, setting up a research laboratory to investigate matters of road construction [82].

Several authors conclude that while WW1 had been an accelerating force for oil, coal had been negatively affected by the conflicts through infrastructural damage, depleted labour supply and labour strikes [3,57,83–86]. According to the official history of the British coal industry, British coal was an ‘industry in decline’ [86]. This is reflected in the writings of Trade Unionist Ivor Thomas, who in 1934 lamented this decline stating that “whether we like it or not, we are entering – or have indeed entered – an oil age” (126) ** p.43. Yet in the UK, the coal industry remained powerful and what was referred to at the time as the “back-to-coal” lobby still had considerable influence (A.C.Hardy quoted in (126)) ** p.43.

Another impact of war relevant to oil transitions, was the emergence of new users capable of operating automobiles or aeroplanes as a result of wartime experience. The war popularised a product that had heretofore been viewed as elitist – automobiles were transformed from niche vehicles to more familiar form of transportation [68]. The military Surplus of aeroplanes created by World War I was also significant in the USA. Some of the 10,000 planes that had been constructed were integrated into civil aviation which was being utilised for mail delivery [70]. While tractors continued to be used on both sides of the Atlantic, growth was modest in both countries [72,75,88,89], however there was an increase in the USA as the Green New Deal was enacted in the 1930s, however it would be during World War II that the ‘petrolification of agriculture’ [90] would take place, as well as acceleration and innovation in the oil industry and oil becoming further embedded into the mobility system.

3.3 Second World War: deepening synergies

We now focus on the Second World War again summarising broad trends and geopolitical developments as well as relevant sociotechnical developments with regards to the conflict.

3.3.1 Broad developments in energy and geopolitics in the Second World War

The Second World War was a global conflict entirely dependent on oil with American forces in Europe using one hundred times more gasoline in World War II than in World War I [60]. In the energy sector, oil supplies to the UK became cut off in 1941 with bombardment from German submarines [91]. A key centred around sustaining constant supplies of oil to Europe from the USA [60,63,92]. The war therefore transformed patterns of energy imports and exports. Before the war, the UK was still one of the world’s main energy exporters. Britain’s reliance on the United States for supplies of oil that emerged during the First World War had dissipated, and the UK sourced much of its oil from countries including Venezuela, Dutch West Indies, Iraq, and Persia. However, shipping routes from these regions

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3 This was apparent even with regards to the British Navy’s new dependence on oil. In 1931 for example, there was even still a lingering debate as to whether the navy should return to coal-fired vessels despite the clear operational advantages of oil-powered naval vessels [123].
were disrupted during the Second World War. As Edgerton points out, even as late as 1940 the British were determined to maintain their oil independence from the USA [93]. However as the war progressed the UK became reliant on the US for 90% of its oil supply, paying for it with assistance through the Lend Lease Programme [94,95].

During the course of the war, the USA began turning attention towards securing future supplies for oil for the post-war era [79]. In 1944 American Geologist Everytt Gower returned from Saudi Arabia to announce that the oil in the region was the ‘greatest single prize in all history’ [60]. Negotiations between Roosevelt and Churchill took place regarding this future oil supply near the war’s end. In secret meetings at the Suez Canal between Roosevelt and Abdul Aziz ibn Saud however, it was established that Britain would not gain control over Saudi’s oil reserves and that Saudi would exist in the American sphere of influence [79]. This moment and subsequent agreements would be decisive in fundamentally altering international energy trade and geopolitics.

It is also worth pointing out, that oil was had a far stronger influence on war strategy during this conflict. Due to its lack of indigenous oil resource and dependence on synthetic fuels derived from coal, Germany sought to acquire oil resource through territorial expansion. The German quest for oil in the Caucuses is considered a motivating factor in the invasion of the Soviet Union, for example [96]. The Allied Oil Campaign put significant resource into destroying German oil infrastructure and refining capacity [59,79,97]. Waging war was now completely dependent on oil resource and global networks of shipping routes and refineries were deepened as the Allied campaign sought to acquire and deliver adequate oil reserves to multiple theatres of war.

We now look from a sociotechnical systems perspective how more specific demand pressures and logistical challenges had implications for the imperative to use oil in energy, food and mobility.

3.3.2 Demand pressures and sociotechnical developments in the Second World War

During World War II the construction of oil infrastructure was rapidly accelerated. In the USA, the ‘little inch’ and ‘big inch’ pipelines were constructed in under a year between 1942-1943 as a means of transporting oil across the US from the South to the North East [98,99]. At the start of the twentieth century, pipe size had been standardized at eight-inches, however this could only move 125,000 barrels a day when a refinery could produce up to 125,000 barrels. As Richard Rhodes points out, solutions in the form of wider pipes and ‘looping’ techniques were already developed but private companies were not prepared to make the requisite investment. However, during the war these innovations in pipeline technologies were put to use. As Johnson notes, “in the endeavour to meet the demand for crude oil and petroleum products on the East Coast, government-financed pipelines embodied technological innovations – particularly with respect to diameter of pipe – that were to have a lasting impact.”(98, p.78). The “big inch” and “little inch” stretched for 1,254 miles across the USA with pumping stations every 50 miles. The ‘Big inch’ pipelines was capable of moving 350,000 barrels of crude daily and it was the largest and longest pipeline ever built up to that time [98]. An Industry pipeline management committee oversaw the expansions of pipelines under the ‘Tulsa Plan’. Over 3,200 miles of new pipeline was dug and laid during World War Two in the US to enable meeting the vastly increased demand during wartime [94].

In the UK, due to the threat of aerial bombardment of road transportation methods of oil transportation, construction began on the Government Pipelines and Storage System (GPSS) in 1940,
with the first phase was completed by 1942. The system connected key locations such as Liverpool docks with Avenmouth’s stretching underground for 220 km, and in 1943 the pipeline system was extended to connect up various airfields in the East of England. These pipelines eventually would supply all of England’s air fields with aviation fuel [91]. This was a significant technological breakthrough given that there was little knowledge of pipeline construction in the UK prior to the war [91,100].

Innovation in the oil sector was stimulated by the changing demand pressures and logistical challenges of war. World War II is referred by some historians as an “air war” [101] or “the bombing war”[102] and during this conflict the aircraft industry was transformed. Innovations in oil production methods, including perfecting “catalytic cracking techniques”, made possible the production of large volumes of 100-octane gasoline [60]. This fuel was in high demand from the burgeoning and now mass-produced aircraft sector, the oil intensity of which increased with the development of jet engines, and four engine bombers. Huge refineries were rapidly built to facilitate the increasing demand for different types of fuel [90]. While this fuel and associated innovations were developed before the war there had been no market for them prior to the conflict [103].

With the “mass mobilisation of science” during World War II [104], A host of other scientific endeavours accelerated during WW2 also had considerable significance for aero-industry. This included advancements in Radar technologies, air precision, electronics, and computing, and cabin pressure. Meanwhile 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). This mass mobilisation of the auto-industry for the war effort would see the sharing of innovation and collaboration around mass production techniques with significance for greater efficiencies in the post-war production of automobiles [105–107]

With immense pressures on agriculture to increase production in the USA and UK, mechanization the use of tractors and combine harvesters increased. For example, in 1939 there were 56,000 tractors in the UK and by 1940 there were 100,000 [72]. In the USA, the number of tractors on U.S. farms rose from almost 1.6 million tractors in 1940 to 2.4 million tractors in 1945 – an increase of two-thirds. Innovations took place in the design of tractors as they were mass produced; tractors got smaller, hydraulic systems were introduced, and they became more powerful. The energy intensity of US agriculture had increased and new innovations such as ‘hybrid corn’ and larger farm sizes would open up the need for fertilisers which were also being rapidly developed during the war to protect troops fighting in the Pacific, dependent on petrochemicals industries that were consolidating as the refining of oil increased [90]. As Boon writes, “higher prices and a seemingly unlimited demand for farm products, combined with a shortage of farm labor and appeals from the government to increase production, led farmers to adopt technological advances” that had entailed increased “input of mechanical power and machinery, fertilizer and lime, chemicals, feed and seed, and other items” (88) ** p.588.

The innovations and acceleration of the development of plastics from petrochemical sources that were accelerated during the Second World War in the USA would have important implications for the food system in post-war developments. In 1937, the first meeting of the Society of Plastics Industry
(SPI) had recognised concluded that there was no market for these products. However, during the war the demand pressures of war meant there was an urgent need to conserve aluminium, copper, steel and zinc for war materiel. These pressures, combined with increased oil production during the war, meant that an opening was created for oil-derived products to further penetrate into areas such as clothing, and storage and as a solution for food preservation and storage. Between 1940 and 1945 production of plastics almost tripled in the USA [108]. As Black notes with regards to the burgeoning plastics industry, “petroleum became a primary component in allowing producers to overcome limits of supply and production”(8) ** p.44.

3.4: towards maturity in the age of oil: Re-orientation, reconstruction and energy abundance

Towards the war’s end, the new condition of future US energy policy was stated by the State Department’s Petroleum Advisor: “[the central objective]...is not a rationing of scarcity, but the orderly development and orderly distribution of abundance.” Quoted in Black (60) ** p.46. In 1950, oil overtook coal as the main source of energy in the USA [109]. The Second World War had been key in transforming the infrastructure associated with oil, and much of this had been achieved through government spending. The US government set about transferring government holdings of pipelines refining capacity and tankers to the private sector [94]. Post war lobbying by the US coal industry to close the “little inch” and “big inch” pipelines on the basis they were at a competitive disadvantage failed [98], and these pipelines open up East Coast America to expanded supplies of oil as well as natural gas [98,110]. In 1945 hours after the Japanese surrender, oil rationing was suspended in the United States which saw consumers “…designing their post-war lives around energy decadence” (99) ** p.401.

In the USA, a key challenge related to the immense productive forces that had been mobilised during total war, entailing “…problem of productive over-capacity and its reconversion into peacetime” (15) ** p.145. The automobile industry stabilised and set about producing cheap cars in record numbers sustaining the high employment achieved in the war years and working with new refined mass production [107,111]. The Second World War had transformed air infrastructure and had left a network of runways equipped with new air traffic control systems and standardised aircraft paving the way for domestic and civil aviation to considerably expand.

Oil flowed through other sociotechnical systems, such as the plastics used in food packaging [112]. The mechanization of agriculture continued and required increasing petroleum to power machinery [113]. Industrial agriculture based on mechanisation, the transportation by truck of agricultural produce became more widespread after the war as large highways were constructed [81]. Oil had seeped into every part of American life, forming an “ecology of oil” where “Oil does not just fuel Americans’ vehicles. Oil has changed their diet, their clothes, their neighbourhoods, their jobs, their fun—in fact, everything about U.S. society” [8]. ** FIND PAGE NUMBER

The situation of continental Europe after World War II was one of extreme scarcity caused by the tragic destruction of war. Production of coal had fallen in the UK and across Western Europe and coal infrastructure, especially in Germany, had been severely damaged [29]. Traditional trade routes and supplies did not return to normal immediately after the war and the industry was in a state of crisis
Although the UK had not been as badly affected as countries on the continent, there were still grave concerns about the depleted coal industry [115].

The UK was now a net energy importer, and set about attempting to reconstruct its industries through nationalisations [116]. Yet, in the early 1950s, the UK’s share of oil began to rise markedly reaching 12% in 1955 from a share of less than 5% at the war’s end [29]. This trend continued and the UK’s imports of rose rapidly through the 1950s. Despite continued attempts to gain control of oil in the Middle East after the Second World War, the UK’s oil imports were largely from Middle Eastern supplies under the sphere of influence of the USA [30].

While this paper has focussed primarily on the USA and the UK, is possible to draw provisional conclusions regarding the rapid transition to oil that occurred across Western Europe in the 1950s identified by several authors [10,11,109] The ‘black gold’ of Saudi Arabia controlled by the USA, was not used initially to fuel American abundance but rather to facilitate the reconstruction of Europe. The solution to the problem of European energy scarcity was, arguably, American abundance. The European Recovery Programme (Marshall Plan) was initiated by the USA in 1948 and 10% of Marshall Plan loans related to the importation of oil to Europe [94,117].

Marshall Aid planning for the European Recovery Programme in 1948 was posited upon a shift towards petroleum usage [117], and 10% of all loans made via the Marshall Plan by the USA were for the purchase of oil [117] It is possible to conclude that the exporting of Saudi oil to Europe influenced The share of petroleum products in the primary energy consumption mix of Europe at the end of the war was around 10% [29]; by 1955 it was 21% and by 1964 it was 45% [29]. In the 1950s several pipelines were built connecting Europe to Mediterranean supply routes from the Middle East and extensive networks of pipelines were built across Europe including the TAP line completed in 1950, Kurkirk-Damascus line in 1952, Inter-Provincial in 1950, and the Trans-Mountain in 1953 [29]. As historians of European infrastructure point out, these European pipeline projects drew on successful wartime experiences with constructing extensive pipeline networks such as the GPSS in the UK [118].

It could of course be argued that the increase in oil consumption in Europe was simply because of cheap price of oil. However, historians highlight that the European oil transition was fundamentally shaped by the USA's new-found global dominance and Cold War concerns about Europe becoming dependent on oil from the Soviet Union. As Boon writes, after the war “neither a distinct Western European Oil regime nor an integrated [European Economic Community] governance framework for energy materialised”. Rather, “…the transition to oil evolved under a global regime dominated by multinational oil companies – then at the apex of their power and closely linked to the informal empires of the US and Britain” (119) ** p.83. The age of oil in Europe was strongly facilitated by innovations and frameworks amplified during the war in the USA that diffused to the European context as oil companies constructed pipelines and refineries and a new network to facilitate many European countries’ rapid transition to oil.

The oil dependence of Europe grew as road mobility, automobiles, and trucking increased as the restoration of Europe’s transport infrastructure took place. There is evidence of the USA’s preference for exporting trucks to Europe rather than rail freight after the war, and strong lobbying by US to push for more prioritisation of road infrastructure construction in European construction [120]., As Seely highlights, the relative ease with which American-style highway and traffic engineering moved across the Atlantic also was a product of the willingness—indeed eagerness—of American engineers, government officials, and industrial leaders to assist in this diffusion process” (121) ** p.230-231. Similarly with regards to the food system, the Marshall plan may be also relevant. Technological transfer of tractors, industrial agricultural techniques, hybrid corns requiring fertilisers and other
innovations that accelerated in the UK and other Western European countries were also encouraged through agricultural support mechanisms as part of the Marshall Plan [122].

We do not make firm conclusions regarding this wider oil transition in Western Europe, but it at least seems plausible as a significant diffusion mechanism in terms of the imperative to use oil. What is clear is that by the end of the Second World War, oil was firmly embedded in the multiple sociotechnical systems and it seems plausible from our analysis that innovations responding to the demand pressures of total war, were an important influencing factor in initiating this process.

4 Discussion: world war in energy transitions and the culmination of the deep transition

We now discuss the broader significance of our interpretive analysis contributing to discussions on the role of war in energy transitions, and the contribution this framework makes to in responding to and developing the deep transitions framework. We also discuss the value of the Deep Transitions (DT) framework focussing on the coordination of multiple sociotechnical systems for energy transitions research.

4.1 World Wars and energy transitions: 3 propositions

Focussing mainly on the USA and UK, we have conducted an interpretive analysis integrating insights from geopolitics and historical literatures on war with a sociotechnical approach focussed on multi-system demand pressures. Under the exceptional demand pressures of total war, the imperative to maintain abundance and constant supply saw the search for solutions to meeting demand challenges, and in both the First and Second World War this process deepened society’s reliance on oil resources. The imperative to use oil became present in multiple sociotechnical systems. With regards to World War I, our analysis corroborates work in energy transitions that has interrogated the key role of the conflict in influencing a shift from coal to oil, where war can be seen as an extreme form of ‘creative destruction’ [3]. This work also chimes with studies of the role of war on energy transitions including hydro-electricity in Canada, the USA, and Germany [1,4,40,41] that highlighted the importance of world wars as mobilising forces for energy transitions.

Given the limitations of our geographical focus, our broader conclusions on the role of war in energy transitions must necessarily be cautious. The pattern of the emergence of the ‘oil age’ at global level does not necessarily fit the time period of the ‘fourth surge’ as depicted by Perez. As Rubio-Varaz highlights in an analysis of Latin American transitions to oil influenced by the First World War, these occurred at a far earlier stage than Europe [2]. However, the stages of the ‘age of oil’ in terms of irruption, frenzy, synergy, and maturity fit with the developmental processes with regards to the USA and UK and Western Europe.

With the existing work on energy transitions and world war in mind, the present analysis can be used to draw out propositions about the role of war in energy transitions and the mechanisms that influence energy transitions. These are not designed as definitive conclusions but rather insights from the present research that could be tested further with different case studies, national contexts, and international dynamics contributing to the emerging literature on world wars and energy transitions. We outline three propositions as follows:
1. **World War amplifies both ‘sides of the coin’ of sociotechnical transitions.** Kivimaa and Kern [53] refer to the creative processes of sociotechnical niches being nurtured and the flip side of destabilisation as both being crucial in understanding transition processes. In this study, the demand pressures of war and the search for solutions to these problems, saw a range of developments taking place during wartime that further embedded oil in multiple systems. This included the acceleration of automobiles and aeroplanes in the First World War, increased mechanisation and tractor use in response to labour shortages in the First World War, and petrochemical solutions to shortages of materials in the Second World War. These technologies and innovations existed prior to the wars however strategic opportunities for their use were opened up by the particular stresses and selection environment of wartime. At the same time, the coal industry, and associated industries in the mobility sector experienced destabilising consequences both in the First World War, which was compounded by the World War II, due to severe disruption of export routes, infrastructural damage, and labour shortages.

2. **World War shapes the international integration of energy systems.** This at first seems counter-intuitive because war is of course divisive, and considerable literature has rightly drawn attention to the tendencies towards a push for greater national self-sufficiency and autarky in energy as a result of war. This is certainly true in some respects, however with the case of oil we see that the UK and other European countries became more tightly bound to the American oil regime during the First World War through the Inter-Allied Petroleum Conference. While in the period of ‘frenzy’ the UK attempted to forge its own path, the integration between the US and British energy systems intensified once again in the Second World War. Through re-orientation and reconstruction, the post-war period saw this integration continue as the UK along with many Western European countries transitioned more rapidly to oil largely controlled by the United States.

3. **Infrastructural Surplus and reconversion.** The foundations of the oil-based society were laid during the Second World War. Extensive pipelines in the USA and the UK built to fuel the war effort were reconverted to supply oil and natural gas to the American East Coast, and aviation fuel to airports for civil aviation in the case of the UK’s pipeline developments. Runways, air traffic control systems, and refined logistics produced during the Second World War were reoriented to civil aviation. The surplus of agricultural produce in the United States had to be maintained in order to ward off economic collapse and petroleum-reliant industrial agricultural practices persisted and intensified to maintain this abundance. After the First World War, a surplus of planes in the US and UK were absorbed into civil airlines, then in their infancy. The First World War created hundreds of thousands of new users of oil-dependent forms of mobility automobiles. The First World War saw many exposed to automobiles and aeroplanes for the first time, and returning to peacetime, those that survived either were more willing to use automobiles or could take up employment in emergent civil aviation sectors or trucking industries.

The role of war in energy transitions can be further explicated by returning to the implications of this analysis for the Deep Transitions framework.

4.2 Deep Transitions and energy
Our analysis, through focussing on the demand pressures of the world wars, and the solutions that emerged to these challenges, has highlighted how in world wars the imperative to use oil was accelerated in all systems by innovations and experimentation. The three systems, energy, food, and mobility – were more tightly integrated as a consequence of wartime activity. Following Schot & Kanger, We have contributed to a deep transitions understanding in terms of “understanding how changes across multiple systems became connected and coordinated, developing a common directionality in the long run” (14) ** p.1046.

While the trend towards oil use accelerated faster in the mobility system after World War I and the growth of mechanised agriculture was modest, during World War II, these systems become even more tightly integrated. Pipeline infrastructure, refinery capacity, petrochemicals, plastics, pesticides, increased mechanisation of agriculture, mass production of airplanes, construction of runways, and a host of other concurrent developments were accelerated by war. In the language of the DT framework [14], the role of war in deep transitions, is the tighter integration and coordination of multiple sociotechnical systems in a similar direction. World War amplified the meta-rule of the imperative to use oil, and shaped the emergence of societies underpinned by oil in numerous domains.

The DT framework can be a useful conceptual tool for energy transitions research more broadly. In focussing on multiple systems, the DT perspective analysis of the age of oil conducted in this paper, reveals the interdependencies between different systems and how they are tied together by oil infrastructure and use. These multi-systemic understandings are useful in thinking about the shift away from an oil-based societies, and the need for multiple policy interventions and policy mixes to enact a deep energy transition based around sustainable sources of energy. The focus on rules and meta-rules can assist in understandings of how broader transitions beyond one sociotechnical system could be influenced as well as the more deep-rooted unsustainable routines and patterns of behaviour that must be undone. The DT framework can also be used to explore the key mechanisms for deepening renewable energy transitions if an ‘ecology of renewable energy’ rather than oil, is to be achieved. This raises questions about looking at wider peaceful mobilising forces that can also decisively and rapidly influence the directionality of energy systems that are not reliant on the tragedy and violence of war. Indeed, given the enduring links between militaries and the oil regime, a focus on demilitarisation may be a more important starting point as we think about prospective sustainability transitions.

5. Conclusion

In this paper we have focussed on the emergence of the age of oil in the twentieth century which forms a core aspect in the culmination of the first deep transition. We have conducted an interpretive analysis drawing on geopolitical and historical literatures to build an understanding of how the exceptional demand pressures and the logistical challenges experienced in multiple sociotechnical systems influenced oil transitions. In the striving to find solutions to demand challenges during war, oil became further integrated into multiple systems both as a fuel source and as a key resource.

Going forward, this analysis suggests that war, often discussed in MLP approaches as a residual landscape factor rather than a focal point of analysis, has a more central role in producing our existing incumbent energy regimes and there should be more attention in sustainability transitions research to unpacking the landscape category and build understandings of the dynamics and mechanisms that different kinds of landscape shocks entail for sociotechnical transitions.
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