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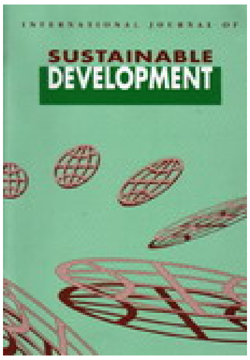

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World War II and its lasting legacy: an overview of socio-metabolic transition, environmental impacts and resource flows

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Abstract: World War II (WWII) was a pivotal catalyst for demographic, economic, industrial and environmental transitions. This paper provides an overview of the socio-metabolic transition in eight key Allied and Axis countries during 1935–1960. Unlike previous studies of WWII's immediate economic and political impacts, or of single countries, we undertake a cross-country comparison and identify the causal mechanisms through which wartime disruptions established new developmental trajectories. Examining prewar conditions, direct wartime impacts and postwar structural change across five dimensions – demography, economy, energy systems, material flows and environmental consequences – we show how WWII catalysed three transition pathways: acceleration, redirection and reset effects. Our analysis reveals how the different political-economic systems emerging from the war mediated these transitions, creating distinctive socio-metabolic regimes with varying resource intensities and environmental impacts. By connecting wartime mobilisation to the 'Great Acceleration', the findings offer insights for contemporary sustainability transitions and governance.

Keywords: sustainability; socio-metabolic transition; material and energy flow; war environmental impacts; World War II; WWII; Great Acceleration.

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1 Introduction

Contemporary climate change and sustainability challenges demand a deeper understanding of the historical processes that have shaped our current resource-intensive societies. The mid-20th century marked a fundamental transformation in human-environment relationships, with the emergence of what has been termed the 'Great Acceleration' – an unprecedented surge in resource use, energy consumption, population growth, and environmental impacts (Steffen et al., 2015). While this transition has been documented widely, the catalytic role of World War II (WWII) in this transition remains unclear. Understanding these historical transformation mechanisms is increasingly important for contemporary policy makers who must design strategies for rapid sustainability transitions while managing complex stakeholder relationships and institutional constraints (Turnheim et al., 2020).

WWII stands as one of the most transformative and consequential events in human history, significantly altering the course of history, reshaping the socioeconomic landscape, and leaving an indelible mark on the environment (McNeill, 2000; Tucker and Russell, 2004). The war catalysed shifts in demographic patterns, economic growth, resource consumption, and political power dynamics that together formed the modern world's foundation. WWII's reverberations have extended beyond the battlefield, influencing technological advancements, cultural norms, and the international order.

Recent studies have highlighted significant consequences on resource use and environmental change from major conflicts (Haberl et al., 2020; Krausmann et al., 2020; Laakkonen, 2017; Tucker and Russell, 2004). The environmental sustainability literature has increasingly recognised the importance of historical path dependencies in shaping contemporary challenges (Fischer-Kowalski and Haberl, 2007; Millward-Hopkins and Oswald, 2021; Wiedenhofer et al., 2019). WWII's socio-metabolic impacts represent a critical, yet underexamined, dimension in understanding human-environment interactions.

WWII's effects on societal transitions have been examined through various academic lenses, each emphasising a different change attribute. Approaches focusing on economic history have emphasised production statistics, gross domestic product (GDP) trajectories, and financial mechanisms (Broadberry and Harrison, 2020; Crafts and Toniolo, 1996). Technological innovation studies have focused on how wartime R&D investments accelerate development across multiple sectors (Edgerton, 2011; Mowery, 2010). Researchers have documented how military imperatives drive innovations that later diffuse into civilian applications, fundamentally altering technologies. These accounts effectively capture the innovation dynamics, but typically underemphasise how these technologies create path dependencies in infrastructure development that persist for decades. On the other hand, institutional change theories analyse how wartime governance transforms postwar economic and political institutions (Eichengreen, 2008a; Ikenberry, 2019). Geopolitical transformation models examine how WWII reconfigures global power relationships and trade patterns (Kennedy, 1988). Environmental-historical approaches investigate war's direct ecological impacts through destruction, contamination, and resource extraction (McNeill, 2000; Tucker and Russell, 2004). While each perspective provides valuable insights, they share a common limitation: insufficient integration of biophysical and socioeconomic dimensions, particularly material and energy flow patterns and their environmental consequences.

Several transition frameworks hold potential for understanding WWII's effects, yet each has proven unable to provide a comprehensive assessment of the war's multidimensional impacts: the multi-level perspective (MLP) conceptualises transitions through interactions between niche innovations, sociotechnical regimes, and landscape pressures (Geels, 2002). Limited extant research has applied MLP to WWII, primarily treating the war as an exogenous landscape shock that destabilised existing regimes and accelerated niche innovations. For example, Schot and Kanger (2018) positioned WWII within a 'deep transition' framework, suggesting it accelerated the diffusion of mass production and consumption systems. However, MLP studies related to WWII are relatively scarce and typically focus on specific technological transitions, rather than broader societal transformations. Path dependency and lock-in theories examine how historical contingencies create self-reinforcing trajectories that constrain future options (Arthur, 1989), but lack frameworks for integrating quantitative material flow analyses with institutional changes. Other relevant frameworks – including technological innovation systems (Bergek et al., 2008), Kondratiev wave theory (Goldstein, 1985), and Panarchy theory (Gunderson and Holling, 2002) – offer complementary perspectives on cross-scale interactions and long-cycle transformations. Collectively, these frameworks are limited by inadequate integration of biophysical-socioeconomic dimensions, insufficient attention to environmental impacts, and weak connections between war-induced changes and longer-term metabolic transitions.

Socio-metabolic transition analyses examine material and energy flows that drive socioeconomic processes and their environmental impacts (Fischer-Kowalski and Haberl, 2007). This approach conceptualises societies as complex adaptive systems that maintain themselves through continuous exchanges with their environments, encompassing all biophysical flows supporting societal functions. This approach is consistent with broader frameworks for analysing sustainability across economic, social, and environmental dimensions (Munasinghe, 2002; Spangenberg, 2005). Evidence from extant studies suggests that major historical events can alter these metabolic patterns significantly (Krausmann et al., 2008a), although the specific impacts of WWII require further investigation to understand their contribution to patterns observed during the Great Acceleration.

Integrating socio-metabolic transitions into WWII research provides several advantages. First, it combines physical resource flows with socioeconomic dimensions, capturing both material and institutional changes (Fischer-Kowalski and Haberl, 2007). Second, it enables systematic comparisons between different countries, revealing both common patterns and divergent trajectories based on particular war experiences, resource availability, and political-economic systems (Krausmann et al., 2016b). Third, it illuminates relationships between immediate war effects and longer-term transition processes, helping to establish causality between wartime mobilisation and postwar developments (McNeill and Engelke, 2016; Schaffartzik et al., 2014). The framework allows for contextualising quantitative data within broader institutional structures, policy frameworks, social changes, demographic factors, and geopolitical dynamics that have shaped resource use decisions.

The socio-metabolic approach specifically illuminates several critical dimensions of WWII's impact:

1 During WWII, unprecedented resource mobilisation led to significant shifts in production, labour organisation, and resource use. The socio-metabolic perspective highlights changes in energy and material flows that supported the war effort, revealing the restructuring of industrial production and resource allocation that were essential for the war economy.

2 The war accelerated energy system transitions, particularly increasing reliance on fossil fuels. Analysing these transitions through the socio-metabolic lens exposes consequences for resource extraction, transportation, consumption, and associated environmental impacts.

3 This framework allows for a nuanced examination of environmental disruptions caused by the war from intense exploitation and destructive technologies.

4 The socio-metabolic framework illuminates the geopolitical dynamics and resource competition critical to WWII strategies and outcomes. By analysing control and access to strategic resources, it helps to better understand the interplay between resource availability, economic power, and military capabilities which were critical to WWII strategies and outcomes.

5 During the postwar period, significant reconstruction efforts and new economic policies emerged. The socio-metabolic framework provides insights into how the war's metabolic legacies, such as continued fossil fuel reliance and industrial infrastructure expansion, influenced postwar socioeconomic and environmental landscapes.

While several extant studies have examined metabolic transitions in specific countries (Gierlinger and Krausmann, 2012; Krausmann et al., 2008b, 2011, 2016a; Schaffartzik et al., 2014; Schandl and Schulz, 2002; West et al., 2014), they mostly have not focused on WWII's role in accelerating or redirecting these transitions and across multiple countries. In this study, we address the literature gaps in understanding WWII's relationship to major societal transitions, including limited comparative analyses, as most studies have focused on individual countries, rather than systematic cross-country comparisons; a fragmented approach, as extant research typically has emphasised either technological, economic, institutional, or environmental dimensions, rather than integrating these perspectives; insufficient qualitative analysis, since many analyses lack assessment of the qualitative parameters – such as policies, social and political factors – and integrate them with quantitative analyses to determine how they affect socioeconomic changes during wars; and unclear connections to the Great Acceleration, as few extant studies explicitly have connected WWII-related transitions to broader patterns in the Great Acceleration.

This study addresses the following research questions: How did WWII alter major participating nations' material and energy flow patterns during the 1935–1960 period? What distinct socio-metabolic transition phases can be identified, and how do they relate to wartime mobilisation, destruction, and postwar reconstruction? How did different nations' socio-metabolic profiles evolve based on their war experiences, resource availability, and political-economic systems? What were these transitions' environmental implications, particularly regarding CO_2 emissions? How do these findings enhance our understanding of the Great Acceleration and contemporary sustainability challenges?

We aim to determine WWII's contribution to the early phase of the Great Acceleration, identify and quantify specific socio-metabolic transitions triggered or accelerated by WWII across key countries, analyse differences and similarities in transition, and extract insights relevant to contemporary sustainability challenges.

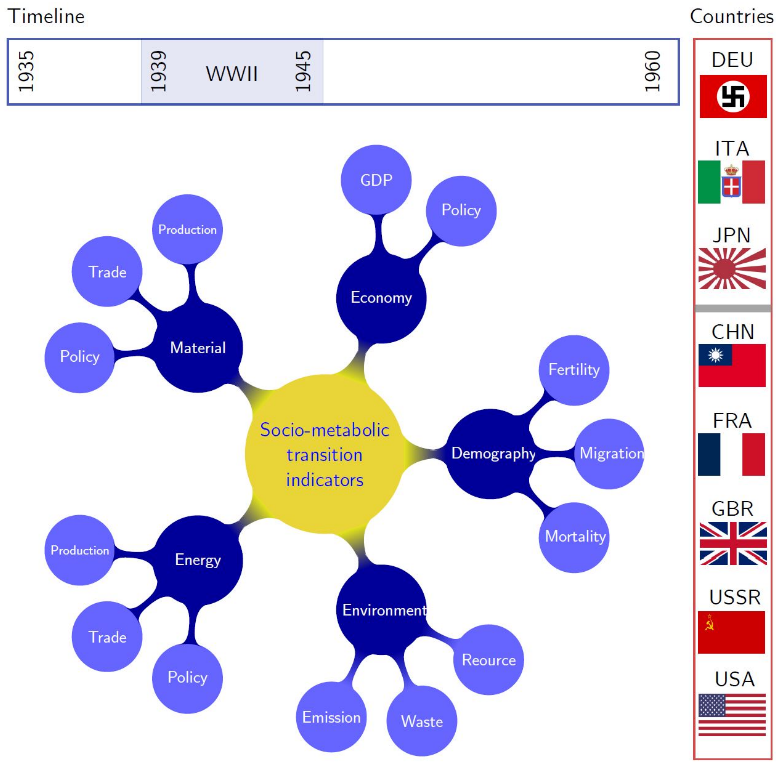
This paper is structured as follows: Section 2 outlines our materials and methods, detailing our framework and analytical approach. Section 3 focuses on socio-metabolic analysis, mainly analysis of trends affected by WWII across demographic, economic, energy, material, and environmental dimensions to determine how WWII impacted these sectors and identify the main mechanisms before, during, and after the war. We then provide country-specific socio-metabolic analyses of eight key countries. Section 4 provides a discussion on comparative analysis and synthesis across countries, WWII, and the Great Acceleration, and discusses our findings' implications for understanding historical transitions and their relevance to contemporary sustainability challenges.

2 Materials and methods

In this study, we applied the concept of socio-metabolic transitions to analyse historical changes in key countries involved in WWII – namely China (CHN), France (FRA), the

United Kingdom (GBR), the Soviet Union (USSR) and the United States of America (USA), i.e., the Allied powers, and Germany (DEU), Italy (ITA) and Japan (JPN), i.e., the Axis powers – during the critical 1935–1960 period. These eight countries cover a range of experiences: victors vs. vanquished; industrialised vs. developing economies; and varying governance systems. Their diverse experiences provide a robust test of how adaptable the socio-metabolic framework is across different contexts. The schematic diagram in Figure 1 provides a summary of the major socio-metabolic transition indicators that we examined in this review article.

Figure 1 Different indicators are studied in this article concerning WWII's effects on the socio-metabolic transition (see online version for colours)



Note: Flags shown represent the nations as WWII participants (Allied and Axis powers). Political entities and national symbols changed during and after the study period; wartime-era flags are used here to reflect the study's focus on WWII and the Allied-Axis in a comparative framework.)

We adopted the socio-metabolic transition framework as our primary analytical lens. Our framework explicitly incorporated crisis-driven acceleration, recognising that wars or other major shocks can alter resource flows and societal priorities abruptly during a short period. Unlike gradualist transition models, this perspective acknowledges that extreme mobilisation during WWII forced societies into new metabolic regimes, such as transitioning from wartime command economies into postwar consumer-industrial economies on unprecedented scales. The socio-metabolic framework offers particular advantages for our analysis, as it integrates physical resource flows with socioeconomic dimensions, enables systematic comparisons across different countries with diverse experiences, illuminates connections between immediate war effects and longer-term transition processes, and captures both material and institutional changes triggered by the war.

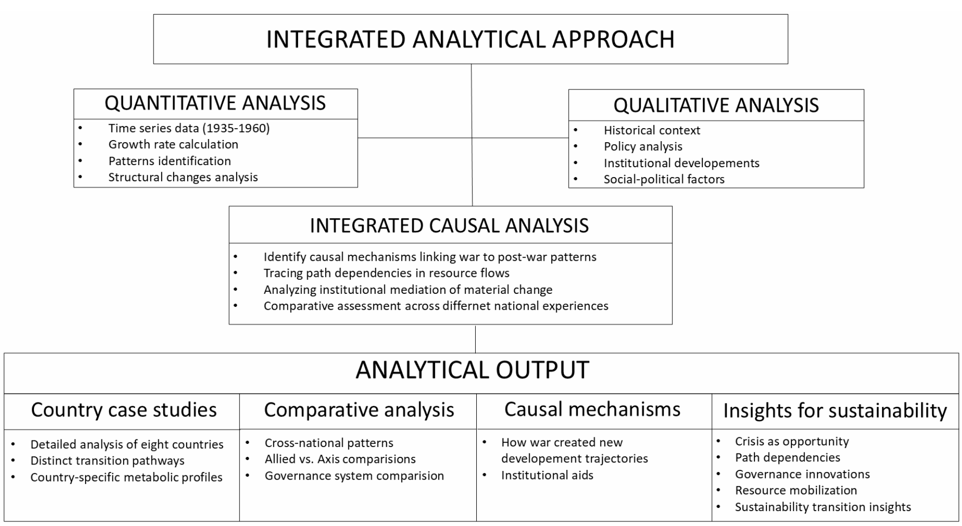
In our analysis, we focused on key indicators directly affected by WWII and its aftermath: energy production (oil, coal, gas, electricity); material production (cement and steel); GDP per capita; population growth; and CO_2 emissions. These indicators were selected for their ability to capture key aspects of industrial capacity, economic resilience, and environmental impact during the examined period. Due to the countries' lack of historical wartime consumption data, we focused on production data to track resource flows. By analysing production data rather than consumption patterns, we were able to observe directly how nations developed their productive capacities during this transformative period. Energy production is a central element in socio-metabolic analysis as it reflects a nation's industrial production capacity and ability to mobilise resources, which are critical during both wartime and postwar reconstruction. Furthermore, fossil fuel production indicates an economy's energy basis. We collected fuel data from Our World in Data, BP Statistical Review of World Energy, and the Shift Data Portal (BP Statistical Review of World Energy, 2025; Our World in Data, 2025; The Shift Data Portal, 2025) and electricity generation data from the book *World Energy Production* by Etemad et al. (1991). Material production data, specifically for cement and steel, is critical due to their roles in industrial activities, infrastructure development, and postwar rebuilding efforts. These indicators provide insight into nations' economic resilience and industrial capabilities during a period of global upheaval. We collected cement and steel production data from several editions of the *Yearbook of the United Nations* (Affairs, 1962; UN Archives Geneva, 1940; United Nations, 1950). GDP and population data provide the socioeconomic context. The GDP per capita serves as an essential metric for evaluating economic growth, quantifying the total value of goods and services produced within a country over a specified period, and trends offer insights into economic development and growth during and after the war, reflecting how nations adapted to and eventually recovered from the disruptions of WWII. Data on GDP per capita were taken from Our World, and books by Maddison and Harrison (Bolt and Van Zanden, 2020; Harrison, 1998; Our World in Data, 2025). The population growth data helped contextualise demographic shifts that influence labour markets, resource needs, and urbanisation patterns, all of which are integral to socio-metabolic transitions. We collected population data from Our World, *Yearbook of the United Nations* and the Gapminder database (Gapminder, 2025; Our World in Data, 2025; UN, 2022). Finally, annual national CO_2 emission trends served as a key environmental indicator, capturing the impact of intensified industrialisation and energy consumption during the Great Acceleration, as well as connecting socioeconomic activities to their long-term environmental consequences. We also collected CO_2 emissions data from Our World and the Global Carbon Project (GCP) (GCP, 2022; Our World in Data, 2025).

Our time frame included the years leading up to, during, and following WWII, including 15 years after the war to account for postwar reconstruction and resilience. Prewar period (1935–1939) data established baseline contexts and trajectories before the war and provided an overview of the late depression and prewar mobilisation period. Data on direct wartime impacts (1939–1945) encompassed immediate disruptions, destruction, and reorganisation of resource flows. Concerning the postwar period (1945–

1960), this period of war-induced structural change enabled us to trace how wartime disruptions created path dependencies that shaped postwar developments and how reconstruction and economic expansion changed societies' metabolic trajectories.

Our methodology combines quantitative and qualitative approaches to provide a comprehensive understanding of socio-metabolic transitions. As for the *quantitative* analysis, we plotted time series for each indicator and country during the 1935–1960 period to visualise trends, identify inflection points, and detect pattern changes associated with the prewar, wartime, and postwar periods. We calculated growth rates across different periods to quantify the pace of change and identify acceleration or deceleration patterns. We examined changes in material and energy production, as well as economic distributions to identify structural transformations in socio-metabolic profiles and to assess how CO_2 emissions were affected. Regarding the *qualitative* analysis, we conducted a structured qualitative comparative analysis of wartime and postwar policies, institutional changes, and social factors for each country to contextualise quantitative trends. We identified distinct phases of socio-metabolic change for each country (prewar adjustment, wartime mobilisation, wartime disruption, postwar recovery, and postwar expansion) based on both quantitative indicators and qualitative historical evidence. We traced causal connections between wartime disruptions, policy responses, institutional changes, and subsequent socio-metabolic patterns to establish mechanisms of influence, rather than mere correlations. Furthermore, we systematically compared governance arrangements, policy frameworks, and institutional innovations across countries to identify how different political-economic systems shaped socio-metabolic transitions. We also incorporated qualitative parameters, including governance and policy shifts (wartime command economies, postwar economic policies, and international aid programs), social structure changes (labour mobilisation, including women in factories; demographic upheavals from casualties and baby booms; and urbanisation), and institutional transformations (new international institutions, Cold War geopolitical divisions, and decolonisation) that influenced resource use patterns. These qualitative factors help explain why quantitative trends look the way they do.

Figure 2 Summary of the study's framework



We specifically examined WWII through several analytical dimensions: resource mobilisation patterns (the unprecedented scale of mobilisation that led to significant shifts in production, labour organisation, and resource use); energy system transitions (accelerations in energy system changes, particularly increased reliance on fossil fuels); environmental disruptions (impacts from intense resource exploitation and destructive technologies); geopolitical dynamics (interplay between resource availability, economic power, and military capabilities); and postwar metabolic legacies (how wartime patterns influenced postwar reconstruction, economic development, and industrial structure).

Our analytical strategy employed several complementary approaches, including *country case studies*, in which we systematically assessed the drivers, patterns, consequences, and socio-metabolic changes for each nation, providing a granular understanding of each country's trajectory; *cross-national comparisons*, through which we conducted cross-national comparisons to identify common patterns, key divergences, and variations in how different countries experienced and responded to WWII, with a particular emphasis on WWII's role in accelerating broader global transitions; *Allied-Axis comparison*, comparing experiences between the Allied and Axis powers, and their contribution to global resource production and emissions; and a *governance system comparison*, in which we assessed how different governance systems handled the war transition. Figure 2 presents a summary of the framework.

3 Socio-metabolic analysis

3.1 Socio-metabolic trends affected by WWII

3.1.1 Demography

Before WWII, the global population was growing steadily, largely due to ongoing industrialisation and urbanisation, particularly in Europe and North America. However, the global economic depression of the 1930s triggered a decline in fertility rates in many industrialised nations (Bacci, 2017; Sobotka et al., 2011). Demographic transitions occurred at varying rates, with industrial nations progressing faster than developing regions. WWII intensified these shifts, causing 70–85 million casualties (3% of the global population of the time), including 50–55 million civilians (Beevor, 2014; Hastings, 2011).

WWII caused demographic changes because of the increased and unbalanced mortality (predominantly affecting young adult males), forced population displacements (involving approximately 60 million people), and a fertility decline (a wartime decline followed by postwar baby booms) (Hobsbawm, 1999; Kesternich et al., 2014). Beyond mortality, unprecedented forced migrations occurred through military operations and deliberate population transfers. These changes affected socio-metabolic patterns by altering the labour availability for industrial development, reshaping household formation dynamics and associated resource demands, redistributing populations spatially, and creating age structure waves affecting consumption patterns over time (Fischer-Kowalski and Haberl, 2007; Kesternich et al., 2014; Krausmann et al., 2008a; Schandl and Schulz, 2002).

WWII's demographic impacts created institutional and social responses that shaped population trends for decades. Three key mechanisms connected wartime demographic disruptions to postwar patterns:

1 *policy responses to population losses*, including pronatalist policies and support for postwar baby booms (Van Bavel and Reher, 2013; Mazower, 1998)

2 *institutional restructuring of migration*, including establishment of the United Nations High Commissioner for Refugees (1950) and the International Organisation for Migration (1951) (Loescher, 2001), which reshaped global migration patterns (Cohen, 2012; Gatrell, 2011)

3 *psychological and social trauma responses*, including what is now recognised as post-traumatic stress disorder (PTSD), which affected family formation and social cohesion (Kesternich et al., 2014; Shephard, 2003), which promoted innovations in psychiatric care and social services.

These institutional responses established governance capacities that shaped resource flows, particularly through housing provision and public health systems, creating path dependencies in material and energy resource relationships (Fischer-Kowalski and Haberl, 2007). Despite the massive wartime losses, the global population grew significantly during the postwar period, from approximately 2.3 billion in 1940 to 3 billion by 1960 (Our World in Data, 2025), reflecting recovery efforts and agricultural/public health improvements. War-created age structures – characterised by pronounced gaps in specific age cohorts due to combat deaths of young males, reduced births during conflict, and post-war baby booms – shaped the economic development, social service needs, and institutional priorities for decades (Dyson, 2010; McNeill, 2000).

From a broader perspective, WWII was a critical juncture, altering demographic transitions across regions. In some areas, postwar fertility recovery and mortality decline reshaped age structures in ways that later supported economic expansion, while in more severely affected regions demographic recovery was delayed, producing different socio-metabolic trajectories through labour shortages, displacement, and altered urbanisation patterns.

3.1.2 Economy

Before WWII, many major economies were still recovering from the Great Depression, with high unemployment, restricted international trade, and significant industrial capacity underutilisation (Eichengreen and Temin, 2000; Irwin, 2011; Romer, 1993). Economic nationalism emerged through protective measures, such as tariffs, currency manipulation, and autarkic policies (Irwin, 2011; James, 2002). Different national responses to the Great Depression created diverging economic trajectories, ranging from New Deal-style intervention in USA to state-led rearmament and industrial mobilisation in DEU and JPN (Eichengreen, 1996; Temin, 1996).

WWII transformed economic systems through unprecedented military resource mobilisation, creating new institutional mechanisms for managing national economies: centralised planning (production boards, rationing, industrial coordination), public-private collaboration models, and international economic cooperation frameworks (Harrison, 1998; Higgs, 1987; Koistinen, 2004; Milward, 1980; Overy, 1994).

The war's economic impact varied across regions. Allied powers, particularly those spared from combat on their home territories, experienced industrial expansion, while occupied countries and combat zones suffered severe economic contraction; while the destruction of infrastructure in Europe and East Asia created opportunities for modernised reconstruction (Crafts and Toniolo, 1995; Harrison, 1998; Overy, 1994; Tooze, 2006).

WWII created economic structural changes through three primary mechanisms:

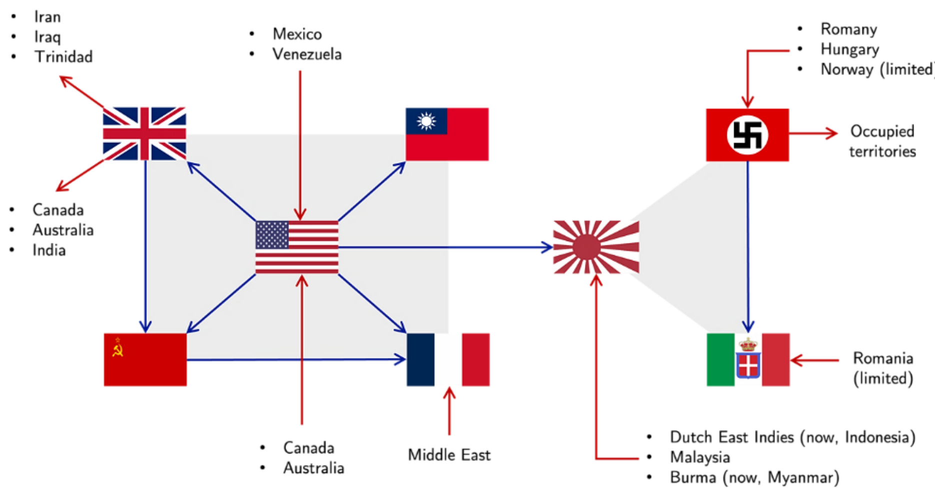
1. *Institutional persistence in wartime governance innovations* occurred as wartime economic institutions continued in modified forms after 1945. Thus, some nations maintained planning mechanisms established for their wartime mobilisation (Hanson, 2014). Others preserved wartime research and development systems, particularly in defence sectors (Mowery and Rosenberg, 1998). These continuities shaped the postwar economic development and influenced socio-metabolic patterns through new resource allocation approaches (Fischer-Kowalski and Haberl, 2007; Harrison, 1998).
2. *An international economic architecture* was established through the Bretton Woods system (1944), which created the International Monetary Fund (IMF), World Bank, and later the General Agreement on Tariffs and Trade (GATT), directly emerging from wartime planning to cultivate postwar stability (Steil, 2013). These institutions were designed to avoid prewar economic nationalism, creating a framework for international economic integration (Gardner, 1980; Ruggie, 1982; van Dormael, 1978). GATT established frameworks for expanded international commerce that facilitated the long-run of global trade and thus material flows (Irwin et al., 2009; Lang, 2013). Regional integration initiatives, such as the European Coal and Steel Community (1951), facilitated new cross-border resource management governance (Gillingham, 1991; Milward, 2000).
3. *The legitimation of Keynesian economic management* occurred as successful wartime demand management and government intervention provided credibility for Keynesian approaches, facilitating more active government roles in economic management, particularly in advanced industrial economies across developed and developing economies (Ikenberry, 1992; Skidelsky, 2001).

Postwar economic recovery followed different patterns across regions, with war-damaged areas generally experiencing more rapid growth during reconstruction. The postwar boom represented a fundamental structural transformation rather than mere recovery. New industrial sectors emerged, consumption patterns shifted, and international relationships reconfigured around new power poles (Armstrong et al., 1991; Hobsbawm, 1999; Judt, 2006). These divergent pathways – market-oriented, mixed-economy, and centrally planned systems – shared common features including expanded state roles, accelerated technological advancement, and increased material throughput, collectively establishing the foundations for the Great Acceleration (Gerschenkron, 1962; McNeill and Engelke, 2016; Rostow, 1990; Steffen et al., 2015).

3.1.3 Energy

Before WWII, coal dominated global energy systems (70% of the world's commercial energy supply in 1935) (Smil, 2010; Podobnik, 2006), while oil was gaining importance, particularly for military applications and transportation (Black, 2012; Yergin, 2008). The energy infrastructure varied significantly, with advanced electrification in industrialised nations supporting industrial growth (Ristuccia and Solomou, 2010; Schurr and Netschert, 1960), while many regions remained largely dependent on traditional biomass energy (Malanima, 2006). Interwar energy strategies also reflected broader concerns about supply security and national self-sufficiency (Painter, 1986).

Figure 3 Fuel imports and exports between countries during WWII (see online version for colours)



WWII catalysed fundamental transformations in energy systems through several key mechanisms:

1 *Infrastructure destruction and relocation*, as strategic bombings destroyed energy infrastructure across Europe and Asia, while military imperatives drove facility relocation, creating opportunities for modernised reconstruction (Collingham, 2013; Landes, 2003). The war severely reduced power generation capacity, affecting both military operations and civilian use (Griffith, 1994).

2 *Innovation in synthetic fuels*, resource constraints spurred massive investments in synthetic fuel technologies to address strategic petroleum shortages, establishing technical capacities that influenced postwar energy technologies (Tooze, 2006).

3 *Accelerated petroleum infrastructure development* became essential as oil's importance drove rapid expansion in strategic production, processing, and distribution (Melosi, 2001; Mowery and Rosenberg, 1998). The USA led global oil production during the war, while the USSR and Venezuela emerged as significant producers (Painter, 1986; Yergin, 2008).

4 *Nuclear technology development* occurred as unprecedented scientific and industrial resource concentration created technical capabilities and institutional models for civilian nuclear energy, driven by projects such as the Manhattan Project (Hewlett and Anderson, 1962; Rhodes, 2012). These projects created new institutional frameworks connecting government, science, and industry (Hecht, 1998).

5 *State control of energy resources increased* as governments took more control over managing energy generation to support war efforts (Foreman-Peck and Waterson, 1985; Jaccard, 1995), including utility nationalisation, consumption rationing, and resource redirection for war materials (Cohn et al., 2020). The war also altered energy trade patterns significantly, as naval blockades severed nations from global oil supplies while new trade routes developed to support military operations (Painter, 1986; Yergin, 2008). Figure 3 shows fuel import and export activity among countries throughout WWII. Blue arrows represent fuel exports (fuel flowing out of a country), and red arrows represent fuel imports (fuel flowing into a country).

The impact of WWII on energy systems extended far beyond the war itself, reshaping global energy patterns through five key mechanisms:

1 *Oil's emergence as a dominant energy source accelerated* as the wartime demonstration of petroleum's strategic advantages accelerated the postwar adoption. The global energy mix shifted as oil gained market share, while coal declined concurrently (Kander et al., 2014; Smil, 2010), reflecting liquid fuel's technical advantages and the massive petroleum infrastructure developed for military purposes.

2 *The development of nuclear power* from wartime nuclear research created both technological foundations and institutional frameworks that enabled civilian nuclear power (Hewlett and Holl, 1989; Rhodes, 2012). The first commercial nuclear power stations (Calder Hall, GBR, 1956; Shippingport, USA, 1957) were developed from wartime research programs (Camilleri, 1984). Building on the atomic research of the WWII-era – exemplified by the Manhattan Project – nuclear power began to emerge as a new electricity source by the 1950s and 1960s and laid the basis for later expansion. Initiatives such as the USA's Atoms for Peace programme expanded civilian nuclear applications further. These arrangements transferred to civilian nuclear power, enabling rapid deployment and significantly influencing electricity generation (Hecht, 1998).

3 *The expansion of a centralised electricity infrastructure*, shaped by wartime experience, helped demonstrate the strategic importance of a reliable electricity supply system and contributed to postwar investment in centralised grid systems. Wartime investments in energy infrastructure – particularly pipelines, refineries, and electricity generation capacity – created physical systems that shaped subsequent energy consumption patterns (Lagendijk, 2008; Nye, 1998).

4 *Institutional persistence in energy governance* continued as countries maintained or expanded wartime institutions; state-owned energy companies built on wartime control mechanisms, while others preserved wartime administration within new regulatory agencies (Foreman-Peck and Waterson, 1985; Mitchell, 2013; Vietor, 1984; Yergin, 2006, 2008).

5 *Strategic concerns about energy security* evolved in the post-war era, informed partly by wartime vulnerability, and increasingly emphasised diversification of supply, strategic petroleum reserves, and new sources such as natural gas, enabled by advances in exploration, production, and pipeline transport (Fouquet, 2016; Smil, 2010; Yergin, 2006). While modern energy efficiency policies took shape mainly

after the 1970s, wartime fuel rationing had already introduced foundational ideas about conserving fuel and rationalising energy use (Smil, 2017).

Post-1945 expansion of refineries, pipelines, centralised electricity grids, and transport networks created the material preconditions for what Pfister (2010) has termed the '1950s Syndrome': a period in which falling relative fossil-energy prices from the late 1950s triggered a massive and inefficient expansion of energy use, driving the production and consumption of energy-intensive materials (Pfister, 2010). The WWII-driven expansion of petroleum infrastructure, electrification networks, and transportation systems, particularly in Europe and JPN, served as essential preconditions for this subsequent acceleration in energy consumption. These developments, varying by region but cumulatively producing a new global energy order, shifted energy systems towards oil, later natural gas, and large-scale electricity infrastructures, driven primarily by industrial expansion rather than environmental goals (Fouquet, 2016; Smil, 2010).

From a transitions and sustainomics perspective, the planning and coordination capacities that states developed to manage large-scale energy system expansion later provided important governance capabilities for steering socio-technical change. Because energy lies at the nexus of economic, social, and environmental dimensions, infrastructure decisions made at such critical junctures had long-lasting effects on growth trajectories, consumption patterns, and environmental burdens (Kern and Markard, 2016; McNeill, 2000; Munasinghe, 2002).

On a general level, WWII accelerated the transition from coal-dominated energy systems towards more diverse energy mixes with significantly higher petroleum components, fundamentally altering global metabolism by enabling more flexible energy applications, higher power densities, and extended supply chains (Fischer-Kowalski et al., 2014; Sieferle, 2001). While specific patterns varied across regions, the general trajectory towards increased fossil fuel consumption, particularly petroleum, represented a shared feature of postwar metabolic development (Haberl et al., 2020; Kander et al., 2014). Post-WWII reconstruction primarily relied on fossil fuels, which accelerated CO_2 emissions (McNeill and Engelke, 2016). In subsequent decades – particularly after the 1970s oil shocks – governments began to shift their attention towards more sustainable energy sources. Nevertheless, WWII-era industrial and infrastructural expansion laid some foundational policy mechanisms, such as centralised planning and large-scale government investment, that later would be repurposed to support sustainability transitions. This war-induced energy transition established the foundation for the dramatic acceleration in global energy throughput that would characterise the postwar decades.

3.1.4 Materials and resource flows

Before WWII, global material extraction and processing systems were recovering from disruptions of the Great Depression, which reduced industrial raw material demand and triggered commodity price declines (Eckes, 1979; Findlay and O'Rourke, 2007; Kindleberger, 1989). Colonial powers maintained preferential resource access from overseas territories, while resource-poor industrial nations increasingly pursued autarky strategies (Overy, 1996; Topik et al., 2006). Material science advanced rapidly, with new manufacturing processes and synthetic materials beginning to supplement traditional resources (Mowery and Rosenberg, 1998; Ndiaye, 2007).

WWII altered global material flows through three primary mechanisms:

1 *Strategic material prioritisation*, as military imperatives required unprecedented mobilisation; allocation boards directed resources towards military requirements, reducing the consumer goods output and introducing widespread rationing (Collingham, 2013; Higgs, 2006; Klein, 2015; Rockoff, 1984). Competition for resource access motivated territorial conquests and strategic campaigns, demonstrating the geopolitical importance of critical materials and establishing supply security as a central policy concern (Barnhart, 1987; Yergin, 2008).

2 *Innovations in material substitutes* occurred, as shortages drove rapid development of synthetic alternatives (synthetic rubber, plastics, fertilisers, pesticides), creating new technological capabilities which transferred to civilian applications (Hounshell and Smith, 2006; Leslie, 1994; Ndiaye, 2007; Russell, 2001).

3 *Resource access strategies evolved* as territorial expansion, motivated by resource competition, reshaped global extraction patterns persisting after the war (Barnhart, 1987; Tooze, 2006).

During the war, strategic bombing targeted industrial facilities and resource processing chains, while nations spared from direct warfare expanded their material processing capacity significantly to meet wartime demands. Recycling and conservation programmes demonstrated the feasibility of more efficient material use and established institutional capabilities for managing material flows that influenced postwar resource management approaches (Cooper, 2008; Strasser, 2000).

WWII created lasting transformations in global material systems through several key mechanisms:

1 *New material governance institutions* evolved from the scarcity management of wartime into peacetime mechanisms, including international commodity agreements (Mikesell, 2011).

2 *Technological transfer from military to civilian applications* – synthetic polymers, light alloys, new construction materials, and agricultural chemicals (nitrogen fertilisers, pesticides) – became fundamental postwar industrial components, altering nutrient cycles and crop productivity (Hounshell and Smith, 2006; Leslie, 1994; Noble, 1984; Perkins, 1997). Aluminium and plastic production, which gained prominence through military applications, became important components of postwar consumer society (Friedel, 1983).

3 *Infrastructure reconstruction with improved materials* enabled countries to incorporate advanced construction methods; the steel industry adopted the basic oxygen process, while cement production incorporated efficiency-enhancing technologies to meet massive demand for rebuilding cities, transportation networks, and industrial facilities (Crafts and Toniolo, 1995; Landes, 2003; Stubbles, 2000).

4 *Military-industrial material networks expanded* permanently after 1945, driven by Cold War competition, and continued to drive innovation in metallurgy, composites, and advanced materials (Alic, 1992; Leslie, 1994).

The global material trade system was transformed likewise. GATT (1947) helped reshape a new material circulation framework, gradually reducing imperial preference systems that dominated prewar resource flows (Irwin et al., 2009). Material supply chains became increasingly global, although Cold War divisions created parallel systems that persisted for decades (Findlay and O'Rourke, 2007; Krausmann et al., 2008a). Agricultural systems also experienced significant war-induced transformations: labour shortages accelerated farm mechanisation and reduced human labour inputs, while food-rationing systems demonstrated the feasibility of coordinated distribution and offered precedents for postwar food governance (Fitzgerald, 2003; Mazoyer and Roudart, 2006).

Overall, WWII accelerated the transition towards more complex, technology-intensive material systems with expanded global supply chains, increasing material diversity, throughput, and network reach beyond prewar patterns. These changes collectively established the material foundations for an extraordinary acceleration in global resource consumption that would characterise the postwar decades, fundamentally altering human-environment relationships across regions (Fischer-Kowalski and Haberl, 2007; McNeill, 2000).

3.1.5 Environmental impacts

Before WWII, many industrial environmental impacts were still perceived mainly as local or regional problems, although GHG emissions and long-range pollutant transport were already beginning to produce broader atmospheric effects that were not yet widely recognised (McNeill, 2000). Industrial pollution affected urban areas and industrial zones in heavily industrialised regions of Europe and North America (Stradling, 1999; Tarr, 1996). Early conservation movements emerged, primarily focusing on preserving natural areas and wildlife, rather than addressing industrial pollution (Nash, 1982). Environmental governance institutions were limited, with minimal regulatory frameworks for pollution control or resource management (Andrews, 2006).

WWII caused direct environmental impacts through several mechanisms:

1 *War-related ecosystem damage* occurred through deforestation, soil disruption, habitat destruction, and coastal ecosystem disruption (Laakkonen, 2017; Russell, 2001; Tucker and Russell, 2004; Westing, 1986).

2 *Industrial pollution intensification* occurred as rapid expansion without environmental controls significantly increased air and water pollution (Closmann, 2009; Markowitz and Rosner, 2002).

3 *Resource depletion acceleration*, as wartime material demands intensified extraction activities with minimal environmental safeguards; mining, forestry, and agricultural activities expanded their geographical footprint, and extraction patterns often established infrastructural arrangements facilitating continued postwar exploitation (Josephson et al., 2013; Krausmann et al., 2009).

4 *Chemical and radioactive contamination* emerged as the military introduced new environmental contaminants – from chemical weapons to radioactive materials – creating contamination hotspots that persisted for decades (Hamblin, 2022).

5 *Agricultural pollution and ecosystem impacts* emerged as labour shortages and disrupted supply chains accelerated the adoption of synthetic fertilisers and pesticides, introducing new contaminants into soil and water systems, while

mechanisation increased fossil fuel consumption and soil compaction (Smil, 2010; Smith-Howard, 2020).

Environmental governance capacity was constrained severely during the war, with resources directed towards military objectives rather than environmental protection (Laakkonen, 2017; Mauch, 2004).

WWII shaped environmental trajectories after 1945 through several key mechanisms:

1 *Accelerated industrial metabolism*, as the postwar boom built on wartime capacity dramatically increased resource throughput – global energy consumption and industrial material use approximately doubled during 1945–1960 (Amouroux, 2015; Krausmann et al., 2009).

2 *The spatial reorganisation of environmental pressures* occurred as wartime industrial relocation and postwar suburban development created new land-use patterns and transportation-related impacts (McNeill and Painter, 2009; Melosi, 2001; Rome, 2001).

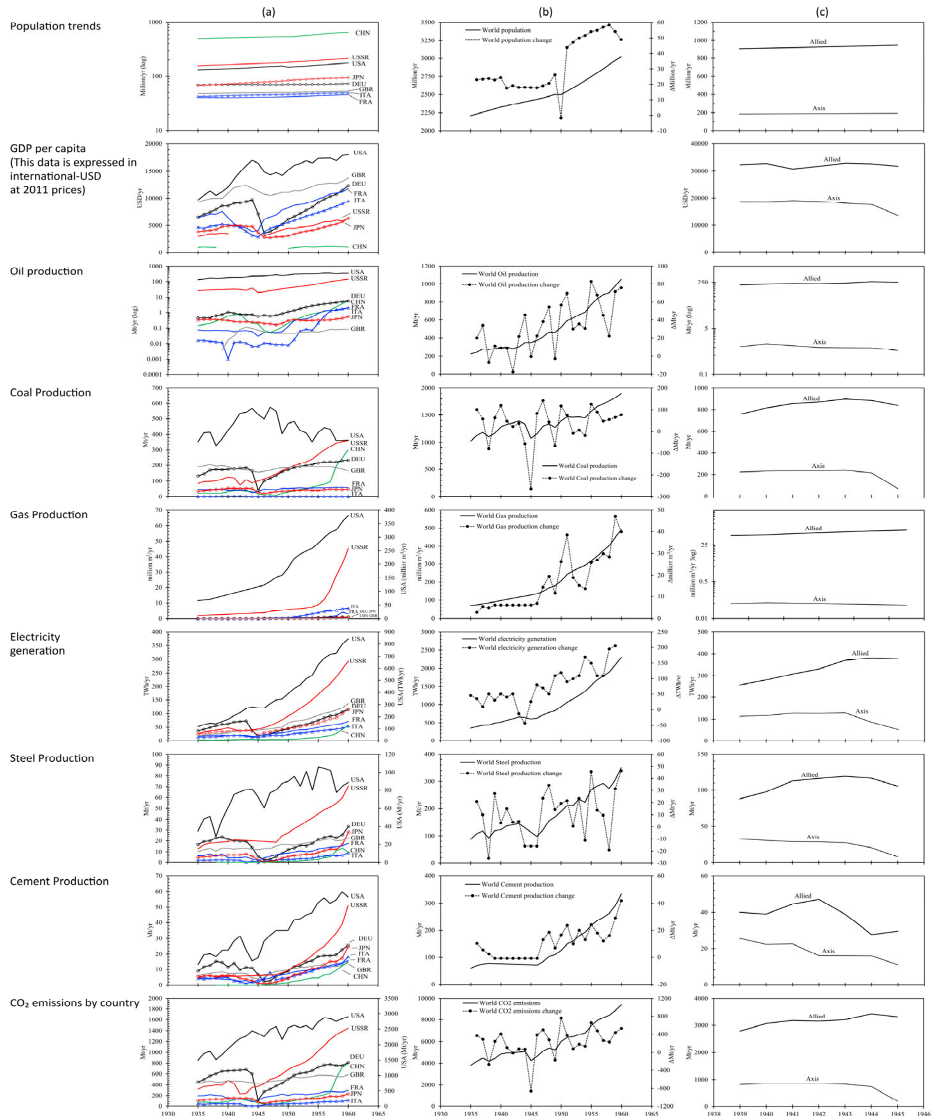
3 *Radioactive hazard awareness* increased as nuclear weapons development and atmospheric testing in the 1950s created heightened awareness of invisible environmental contamination, representing one of the first global environmental issues to gain widespread public attention and contributing to the broader environmental consciousness that developed more fully in the 1960s and 1970s (Hamblin, 2022; Prăvălie, 2014; Weart, 2008).

4 *Technology transfer and infrastructure lock-in*, as wartime innovations in chemical processing, materials science, and propulsion systems brought their associated environmental impacts into peacetime production, while infrastructure reconstruction established long-lived physical structures that shaped settlement patterns, transportation systems, and energy consumption for decades (Josephson, 2002; Krausmann et al., 2010).

The war's environmental legacy included profound impacts on GHG emissions through multiple pathways: industrial carbon intensification created persistent carbon-intensive pathways (McNeill and Engelke, 2016); increased emissions of non-CO_2 greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) beyond CO_2 (Russell, 2001; Tian et al., 2019); agricultural intensification, which raised N_2O emissions through nitrogen fertiliser use; vehicle-oriented infrastructure, which established long-term emission trajectories that were difficult to redirect (Koistinen, 2004); and land use change emissions – from combat operations and bombing campaigns – in addition to postwar reconstruction, triggered significant land use changes, releasing stored carbon from ecosystems and establishing new land development patterns that continued to drive emissions through habitat conversion (Laakkonen, 2017).

Global CO_2 emissions illustrate the war's environmental legacy: between 1945 and 1960, global CO_2 emissions nearly doubled, reflecting postwar industrial expansion and the accelerated transition from coal towards petroleum and later natural gas, which reshaped not only the quantity but also the geographical distribution of carbon emissions (Pfister, 2010; Smil, 2010, 2017). Early environmental policy responses emerged – air pollution controls in response to severe incidents – although comprehensive action would not emerge until the 1970s (Dunlap, 2014; Hays, 1989; Stradling, 1999). The broader environmental awareness movement of the 1960s–1970s represented, in part, a reaction against the resource-intensive development trajectory established during postwar reconstruction (Guha, 2000; Rome, 2003).

Figure 4 Socio-metabolic trends affected by WWII during the 1935–1960 period: (a) in key countries (b) annual global trends in left axis and year-on-year absolute change in right axis, (c) Allied and Axis powers trends (see online version for colours)



Note: Where large disparities between series would otherwise render smaller values unreadable, logarithmic scales or secondary y-axes are used; these cases are indicated on the respective axis labels.

Source: BP Statistical Review of World Energy (2025), Our World in Data (2025), The Shift Data Portal (2025), Etemad et al. (1991) and Pinto et al. (2023)

Taken together, WWII represents a pivotal transition point in human-environment relationships, demonstrating humanity's capacity for both environmental destruction and rapid sociotechnical innovation, and establishing precedents for large-scale environmental modification that would characterise the Great Acceleration (Bonneuil and Fressoz, 2017; McNeill and Engelke, 2016; Steffen et al., 2015). While not immediately apparent during the postwar period, the resource throughput acceleration triggered by wartime mobilisation and postwar reconstruction established consumption patterns that significantly exceeded prewar levels, representing not merely a return to prewar trends but a fundamental shift towards more resource-intensive consumption that would eventually generate global-scale environmental challenges. Understanding these connections between wartime disruption and subsequent environmental trajectories provides an important context for addressing contemporary sustainability challenges.

In the next section, we provide an overview of the socio-metabolic of eight key countries involved in WWII and examine the rate changes of each parameter of these countries. Figure 4 presents different parameter trends during the 1935–1960 period. We will discuss these trends in detail in the next section.

3.2 Country-specific socio-metabolic analyses

3.2.1 China (CHN)

CHN's socio-metabolic transition between 1935 and 1960 illustrates a profound disruption, followed by revolutionary transformation. This transition was shaped primarily by warfare during the 1937–1949 period, which created conditions for subsequent socialist industrialisation policies under Mao Zedong, which were implemented after 1949. This transition can be understood through three distinct phases: prewar agrarian conditions; wartime devastation; and postwar socialist industrialisation. In the mid-1930s, CHN was predominantly agrarian, with minimal industrialisation concentrated primarily in treaty port cities like Shanghai and Japanese-controlled Manchuria (Feuerwerker, 1996; Wright, 2008). Although some industrial infrastructure existed – particularly coal mining, textile manufacturing, and modest steel production – CHN's per capita energy and steel consumption remained extremely low compared with JPN and European nations. Over 80% of its population relied on traditional biomass fuels, such as wood and crop residues, for its energy needs (Sands, 1990; Smil, 2019). Based on the socio-metabolic regime framework by Krausmann et al. (2016b) prewar CHN can be characterised as having a distinctly agrarian, biomass-dominated metabolic profile, with domestic material consumption of roughly three to six tons per capita – among the lowest of the major nations – rather than industrial materials.

During the 1937–1949 period, intense conflicts severely disrupted CHN's socio-metabolic systems. Beginning with the Second Sino-Japanese War (1937–1945) and continuing through the Chinese Civil War (1945–1949), this era witnessed systematic destruction of CHN's production capacity (Eastman, 2002). The Japanese invasion devastated agricultural productivity and either destroyed or appropriated significant portions of CHN's nascent industrial base (Esherick and Wei, 2014; van de Ven, 2018). The impact on industrial output was severe – cement production plummeted from 50 kt (0.05 Mt) in 1940 to 25 kt (0.025 Mt) in 1941, while electricity generation declined significantly. Japanese forces systematically looted resources, dismantled industrial facilities, and crippled the transportation network, particularly railways. By the end of

WWII, industrial production had collapsed, and human losses were staggering, with estimates ranging between 15–20 million lives lost during WWII alone (Mitter, 2013).

The post-WWII civil war between Nationalist and Communist forces exacerbated this socio-metabolic crisis further (Westad, 2003). Infrastructure damage intensified, hyperinflation destabilised the economy, capital fled the country, and economic stagnation persisted, leading to further declines in per capita energy consumption (Chou, 1963; Schran, 1976). When the People's Republic of China was established in 1949, it inherited an economy severely depleted by over a decade of continuous warfare (Lardy, 1984).

The Communist Government implemented a state-directed socio-metabolic transition explicitly modelled on Soviet industrialisation (Meisner, 1999; Riskin, 1988). This transition proceeded through two distinct phases.

First, land reforms (1949–1952) redistributed agricultural land, temporarily improving grain production and freeing surplus labour for industrial projects (Hinton, 2008; Wong, 1973). The First Five-Year Plan (1953–1957), supported extensively by USSR expertise and financial aid, targeted heavy industries, including steel, coal, cement, machinery, and electricity generation (Chan, 2000; Cheng, 2020). This phase elicited remarkable success in establishing industrial capacity, with steel output climbing from negligible levels in 1949 to approximately 5 Mt by 1957. Major infrastructure projects – including expansion of the Anshan steel complex, construction of thermal power stations, and significant hydropower projects, such as the Fengman and Sanmenxia dams – accelerated industrial growth and fundamentally altered CHN's socio-metabolic profile.

Social restructuring accompanied this industrial transformation. Land reform redistributed land to peasants, enhancing agricultural productivity (Shue, 1980). Simultaneously, new central planning mechanisms, such as the household registration (*hukou*) system, directed labour flows and managed urban growth (Chan and Zhang, 1999; Walder, 2017).

The second phase, the Great Leap Forward (GLF; 1958–1960), represented an ambitious attempt to accelerate industrialisation rapidly, but resulted in severe inefficiencies and devastating human consequences (Walder, 2017). Although coal production reached 300 Mt and cement production rose dramatically, to 15 Mt by 1960, these figures concealed significant inefficiencies stemming from mass mobilisation campaigns, particularly the infamous backyard steel furnaces and poorly managed agricultural collectivisation. The result was the Great Chinese Famine (1959–1961), which caused massive loss of life, reduced labour productivity, and slowed population growth (Ashton et al., 1984).

Despite these severe setbacks, CHN's socio-metabolic profile had undergone a significant transformation by 1960. For most industrial indicators, CHN's 1939 prewar levels were negligible (steel: 0.001 Mt; cement: 0.05 Mt), reflecting an agrarian economy with minimal industrial capacity. For coal, oil, and electricity, where prewar production was more substantial, growth is calculated over 1939 prewar levels following the convention used for the other country cases. There were a number of key changes:

1 Energy transition: coal became the primary energy source. Coal production, which had declined 24% below its 1939 level of 25 Mt during the conflict, regained prewar levels by 1950 and reached 300 Mt by 1960 (1,111% above 1939 prewar and 2,500% compared with 1946 levels). While WWII and the Japanese occupation severely disrupted domestic supply chains, the surge in production was driven primarily by

post-1949 industrial policies. Thus, the war's effect was indirect – impairing earlier industrial growth – while postwar recovery and state-led expansion spurred remarkable coal output growth (Cheng, 2020; Naughton, 2007).

2 An emerging petroleum sector: oil production which had fallen 54% below its 1939 level during the war, regained prewar levels by 1952 and grew to 5.5 Mt by 1960 (1,332% above 1939 prewar levels), particularly after early discoveries, such as the Daqing field in 1959.

3 Electrification: generation capacity expanded dramatically, from negligible levels to 58 TWh by 1960 (a 2,010% above 1939 prewar levels and a 1,500% increase during the postwar period), supported by thermal and hydroelectric projects (Potter, 2023).

4 Industrial materials: steel output rose from virtually nothing during the prewar period to approximately 13 Mt by 1959, while cement production followed a similar trajectory, although both experienced inefficiencies during the GLF period (Naughton, 2007).

Environmentally, CHN's CO_2 emissions, which had declined from 74 Mt in 1939 to 36 Mt in 1946, regained prewar levels by 1950 and reached approximately 800 Mt by 1960 (970% above 1939 prewar levels), driven by transitions from agriculture to industrialisation. Environmental considerations were subordinated to output goals, as evidenced by campaigns such as the 'Four Pests', which significantly disturbed the ecological balance, while the GLF contributed to soil degradation (Economy, 2010).

CHN's socio-metabolic transition during the 1935–1960 period illustrates how WWII functioned at a critical juncture – not by directly causing subsequent developments, but by disrupting existing structures and reshaping the conditions under which postwar political and industrial reorganisation occurred (Mitter and Moore, 2011). In CHN proper the Japanese invasion dismantled much of the nascent industrial system, yet in occupied Manchuria it simultaneously built a concentrated heavy-industrial base – centred on the Anshan steelworks, the Fushun coal mines, and large hydroelectric installations – that by 1945 accounted for the bulk of Chinese steel, electricity, and cement capacity. Much of this capacity was stripped and removed by Soviet forces in 1945, but what remained became the industrial core the new state inherited. Post-1949 Communist policies then drove industrial development along pathways shaped by both this wartime destruction and the industrial legacy the occupation left behind (Bramall, 2008). This case demonstrates how war can function as a reset mechanism, creating space for entirely new developmental trajectories, rather than merely accelerating existing ones. The Communist revolution might have occurred without WWII, but its timing, nature, and subsequent industrialisation strategy were influenced significantly by the socio-metabolic disruptions caused by the Japanese invasion and occupation.

3.2.2 France (FRA)

FRA's socio-metabolic trajectory during the 1935–1960 period was affected by its defeat and occupation during WWII, which catalysed comprehensive institutional transformations that fundamentally reshaped the nation's resource flows.

Before the war, FRA's economy relied predominantly on coal, steel, and traditional heavy industry. Despite its status as a major industrial power, the French economy operated within a context of limited industrial dynamism and structural weaknesses that had persisted during the interwar period (Caron, 2014). Its industrial architecture was relatively traditional, with limited innovation in key sectors compared to other major powers, such as DEU and the USA. Long-term material flow analyses by Magalhães et al. (2019) document FRA's metabolic trajectory since 1830, showing that FRA's domestic material consumption stood at approximately 8.5 t/cap/yr in 1939, still dominated by biomass (4.5 t/cap), with fossil energy carriers (1.6 t/cap) and non-metallic minerals (1.9 t/cap) as secondary components, reflecting a metabolism that remained less dynamic than that of its major European competitors (Magalhães et al., 2019).

The German occupation (1940–1944) severely disrupted FRA's industrial metabolism, causing dramatic production collapses across key sectors. Steel production declined by 61%, falling from 8 Mt in 1939 to 3 Mt in 1944. Cement output dropped by 62% (from 4 Mt to 1.5 Mt), while coal output decreased by nearly half, from 50 Mt to 26 Mt. The human and physical tolls were equally severe. The occupation caused severe human losses (approximately 600,000 military and civilian deaths) and led to extensive forced labour under the Service du Travail Obligatoire (STO), which dispersed French workers to German factories. Widespread destruction of critical infrastructure – including railways, ports, and bridges – occurred throughout the occupation, with particularly heavy bombing in 1944 as Allied forces advanced (Jackson, 2003). The war also severely restricted colonial resource flows, disconnecting FRA from crucial overseas supplies that had previously supported the metropolitan economy (Duiker, 1986; Thomas and Brennan, 2017).

The devastation caused by the war provided a decisive impetus for structural change. The defeat and occupation weakened the standing of the prewar economic elites and triggered a strong political consensus on the need for extensive modernisation (Gildea, 2009; Kuisel, 1981). This consensus directly led to postwar policies characterised by active state intervention and planning, most notably through rapid nationalisation of vital industries. Key sectors – including coal (Charbonnages de France), electricity and gas utilities (EDF, GDF in 1946), railways (SNCF, state-owned since 1938), and automobiles (Renault, nationalised in 1945) – came under direct state control. This centralisation enabled coordinated and efficient reconstruction efforts that would have been difficult to achieve through fragmented private enterprise (Andrieu et al., 1987; Kuisel, 1981).

Central to FRA's immediate recovery was the Monnet Plan (1946), a state-led modernisation initiative that sought rapid increases in coal, steel, cement, electricity, transport, and agricultural production. Named after Jean Monnet, who later played a pivotal role in European integration, the plan established production targets and coordinated investments across strategic sectors. Marshall Plan aid significantly bolstered the Monnet Plan, with FRA receiving over \$2.5 billion between 1948 and 1952. As Gross et al. (2022) demonstrate, the European Recovery Programme (ERP) not only accelerated reconstruction but actively drove FRA's petroleum dependency, with petro-aid of \$420.9 million financing crude oil deliveries and refinery expansion through the OEEC's Refinery Expansion Programme (Gross et al., 2022). This substantial external financing accelerated reconstruction efforts, allowing FRA to surpass its prewar industrial output levels by 1950 (Hoffmann and Maier, 1984; Lynch, 2006). By this milestone year, steel production reached approximately 9 Mt (10% above prewar levels), cement output reached 7 Mt (83% above prewar levels), and electricity generation increased by 50%, reaching 33 TWh. Steel production, which had collapsed to 1.7 Mt by 1945 (a 79% wartime decline from 1939 levels), regained its 1939 level by 1949 and reached 18 Mt by 1960 (122% above 1939 prewar levels). Cement output, which fell to 1.5 Mt during the occupation (62% below 1939 levels), surpassed prewar levels by 1947 and reached 16 Mt by 1960 (304% above 1939 levels). Electricity generation, which declined to 16 TWh in 1944 (27% below 1939 levels), regained prewar levels by 1946 and reached 72 TWh by 1960 (228% above 1939 levels).

The postwar recovery transitioned smoothly into a broader socio-metabolic transformation during what became known as 'Les Trente Glorieuses' – the three decades of sustained economic expansion – starting around 1950 (Gildea, 2009). During this era, FRA diversified its energy sources significantly, gradually shifting from its traditional reliance on coal towards oil and natural gas. Coal production, which had fallen from 50 Mt to 26 Mt during the occupation (48% below 1939 levels), regained its prewar level by 1949 and peaked at approximately 60 Mt by 1958 under the management of Charbonnages de France, before declining slightly to 57 Mt by 1960 (15% above 1939 prewar levels). However, coal's relative importance in the French energy mix steadily declined. Domestic oil production increased dramatically from negligible amounts (0.1 Mt in 1950), to about 2 Mt in 1960. Natural gas also emerged as a meaningful energy resource, expanding rapidly to reach 30 TWh by 1960. The coal industry, despite briefly recovering to peak at approximately 60 Mt by 1958, increasingly faced structural challenges from resource depletion and competition from cheaper Ruhr coal available through the newly formed European Coal and Steel Community (ECSC) (Reid, 1985). This European integration, facilitated directly by postwar reconciliation between FRA and DEU, was itself an indirect outcome of WWII.

Electrification also expanded considerably, largely driven by state-led investments in hydropower, which increased electricity production to 228% from prewar levels by 1960. By the mid-1950s, the EDF's rural electrification programmes had succeeded in providing electricity to virtually all French villages, significantly raising standards of living and productivity nationwide. These technical advances were supported by sustained population growth – from 40 million in 1939 to 45 million by 1960 – and a boom in consumer demand. The proliferation of affordable automobiles, such as the Renault 4CV and Citroën 2CV, alongside increasing household appliance ownership, symbolised FRA's entry into mass consumer society (Ross, 1995).

The war-driven restructuring was accompanied by significant agricultural modernisation, including increased mechanisation and widespread use of chemical fertilisers. These changes raised agricultural yields and freed labour for growing urban industrial sectors (Duby, 1978; Mendras, 1972). Furthermore, decolonisation processes accelerated by WWII altered FRA's resource strategy, shifting reliance away from direct colonial extraction and towards international market integration, a transition exemplified by brief access to Saharan oil during the Algerian War (1954–1962) (Ageron, 1991; Shepard, 2006).

By 1960, FRA had emerged as a prosperous, technologically advanced industrial economy, successfully diversified away from its prewar reliance on coal and steel, and towards oil, natural gas, electricity, consumer manufacturing, and modern infrastructure. The GDP per capita, which had fallen to $3,861 during the occupation (49% below 1939 levels), regained its prewar level by 1949 and rose to $11,792 by 1960 (54% above 1939 prewar levels), underscoring substantial improvements in living standards. This transformation represented a fundamental shift in FRA's socio-metabolic profile, marking the transition from biomass and coal-dominated industrial metabolism documented by (Magalhães et al., 2019) towards a petroleum-based consumer economy.

However, this transformation's environmental impacts were mixed. FRA's CO_2 emissions, which had fallen to 80 Mt in 1944 (60% below 1939 levels), regained prewar levels by 1948 and reached 296 Mt by 1960 (52% above 1939 prewar level). Industrial expansion and increased consumption fuelled postwar growth. Although this rapid industrial expansion created environmental challenges, such as urban air pollution and river contamination, early investments in hydropower and initial nuclear power at Marcoule (from 1956 onward) inadvertently positioned FRA on a path towards lower carbon intensity relative to exclusively fossil-based economies (Hecht, 1998; Vaubourg, 2004).

The French case illustrates how, in this particular context, wartime defeat and occupation created conditions that facilitated substantial institutional reorganisation. FRA's post-war transformation illustrates a potential pathway through which military defeat can, under certain circumstances, enable institutional change by discrediting previous governance structures. The war thoroughly discredited previous governance approaches while simultaneously creating political conditions conducive to state-led economic coordination that directly reshaped resource flows and metabolic patterns. These institutional changes – the growth of state administrative capacity and implementation of economic planning mechanisms in FRA's specific case – proved more significant for long-term socio-metabolic development than the physical destruction caused by the war itself. The war created a critical juncture that enabled FRA to overcome prewar institutional inertia and establish new governance arrangements that would guide its socio-metabolic development for decades afterward. As (Gross et al., 2022) demonstrate, the interaction between domestic institutional reforms and external capital flows – particularly the ERP and OEEC's role as a system entangler linking energy, agriculture, and transport sectors – was instrumental in redirecting FRA's energy metabolism towards petroleum dependency. Material flow data from (Magalhães et al., 2019) confirm the scale of this transformation: FRA's DMC grew at a rate of 4.36%/yr during 1948–1960, with the per capita consumption rising from 7.8 to 11.7 t/cap/yr. This was driven particularly by non-metallic minerals for construction and infrastructure, alongside growing biomass and fossil energy carriers, illustrating how postwar recovery mechanisms simultaneously enabled economic modernisation and established long-term path dependencies in fossil fuel consumption.

3.2.3 Germany (DEU)

DEU's socio-metabolic trajectory during the 1935–1960 period demonstrates how total defeat and subsequent division created a decisive rupture in resource use patterns, followed by distinct reconstruction paths shaped by competing political-economic systems. This case offers insights into how similar wartime experiences produced divergent post-war socio-metabolic trajectories in East and West Germany when shaped by specific governance systems. The contrasting political-economic frameworks – namely, the market-oriented system versus centrally planned socialist economy – led to significantly different resource utilisation patterns despite shared wartime destruction.

The prewar Nazi regime mobilised an intensive metabolic surge characterised by a rapid expansion of strategic industries to support military preparedness and economic autarky (Weinstein and Hayes, 2002). This mobilisation created dramatic growth across key industrial sectors. Between 1935–1939, steel production increased by 44% (from 16 to 23 Mt), electricity generation rose by 67% (from 36 to 60 TWh), and synthetic oil production which was central to DEU's self-sufficiency strategy (Stokes, 1985), nearly doubled, from 0.4 to 0.7 Mt. These developments represented a deliberate state-led transformation of DEU's industrial metabolism to support military ambitions, with a particular emphasis on strategic resources that DEU could not access easily through international trade. Langthaler (2023), analysing how the Nazi regime shaped resource use patterns in Austria from a socio-ecological perspective, describes this process as an 'interrupted acceleration' – a pattern applicable to DEU, where the regime's intensive resource mobilisation established metabolic trajectories that were violently disrupted by the war itself, yet left lasting imprints on postwar reconstruction patterns (Langthaler, 2023).

WWII significantly reshaped DEU's metabolic patterns through several distinct phases. Initially, the DEU war economy maintained high production levels despite Allied bombing campaigns, as the occupied territories provided additional resources and labour. However, as the war progressed, the combined pressures of intensifying resource scarcity, escalating strategic bombing of industrial centres, progressive territorial losses, and labour shortages ultimately caused a dramatic collapse of DEU's industrial metabolism by 1945. The scale of this metabolic disruption was extraordinary: coal and steel production decreased by 77%; electricity generation fell by 71%; and cement production decreased by 54% compared to the 1939 level. The physical consequences were catastrophic: cities were reduced to rubble; transportation networks were destroyed; industrial capacity was decimated; and millions dead (Despres, 1946; Kroener et al., 2000; Milward, 1965). This destruction created a profound discontinuity in DEU's socio-metabolic development.

The postwar period was characterised first by the Allied occupation and then by DEU's division into West Germany and East Germany following the establishment of the Iron Curtain, with fundamentally different political-economic systems on each side of the curtain. This bifurcation created a natural experiment in socio-metabolic development, as similar starting conditions evolved along divergent trajectories shaped by competing institutional arrangements. West DEU benefited from a combination of internal reforms and external support that facilitated rapid recovery and eventual prosperity. The 1948 currency reform (the introduction of the Deutsche mark) stabilised the monetary system and eliminated the black market economy. Market liberalisation policies championed by Ludwig Erhard created conditions for private enterprise. Substantial Marshall Plan aid (over $1.4 billion between 1948 and 1952) provided crucial capital for reconstruction (Abelshauser, 1975; Maier and Bischof, 1991). These factors collectively catalysed the Wirtschaftswunder, or 'economic miracle' characterised by rapid industrial expansion, particularly in the steel, cement, and electricity sectors (Nicholls, 2000). By 1960, DEU had achieved a remarkable recovery. Steel production, which had collapsed to 6 Mt by 1945 (76% below 1939 levels), regained its prewar level by 1957 and reached 33 Mt by 1960 (41% above 1939 prewar levels). Cement production, which fell to 7 Mt in 1945 (54% below 1939 levels), regained prewar levels by 1953 and reached 26 Mt by 1960 (76% above 1939 levels). Coal production regained its 1939 level by 1951 and reached 234 Mt by 1960 (36% above 1939 levels). Electricity generation, which had fallen to 18 TWh in 1945 (71% below 1939 levels), regained prewar levels by 1954 and reached 116 TWh by 1960 (90% above 1939 levels). Integration into Western institutions – particularly the European Coal and Steel Community (ECSC) in 1951 and NATO in 1955 – reinforced industrial expansion further by providing secure access to resources and export markets. West DEU's energy mix diversified beyond coal to include imported oil and emerging petrochemical industries, supporting more efficient industrial production (Berghahn, 1986; Hoerber, 2017).

However, under Soviet influence East DEU followed a markedly different reconstruction path. It faced an initial economic handicap from USSR reparations (approximately 30% of industrial assets). The East German state adopted a socialist economic model emphasising heavy industry, central planning, and collective ownership through People's Owned Enterprises (VEBs) (Kopstein, 1997; Naimark, 1997). The First Five-Year Plan (1951–1955) prioritised iron and steel, chemical plants, and extensive exploitation of domestic lignite coal reserves (Steiner, 2010). East DEU's resource constraints shaped its distinctive energy profile. Limited access to oil (mostly Soviet-supplied) led to a heavy reliance on lignite coal, which dominated its energy mix despite significant environmental impacts. While achieving notable recovery in specialised industries – including optics, machinery, chemicals, and electricity production (becoming a significant electricity exporter within the Eastern bloc) – East DEU's economy suffered from central planning inefficiencies, resource-intensive production methods, and persistent consumer goods shortages. These systemic challenges created social and economic strains that culminated in the June 1953 uprising and subsequent mass emigration to West DEU, thereby complicating recovery efforts further (Naimark, 1997; Steiner, 2010).

By 1960, the country achieved a remarkable recovery, with combined GDP per capita, which had fallen to $7,195 during the war (17% below 1939 levels), regaining its prewar level by 1955 and reaching $12,282 by 1960 (43% above 1939 levels), despite territorial and population losses. However, this apparent recovery masked a profound divergence between the two German states. West DEU developed a highly efficient, export-oriented, market-driven metabolic system characterised by rapid motorisation, extensive infrastructure development, and growing consumer prosperity, while East DEU maintained a more rigid, resource-intensive socialist system with a narrower industrial focus, slower modernisation, and limited consumer goods production (Carlin, 2010; Eichengreen, 1994).

The environmental conditions also diverged significantly between the two states. West DEU began experiencing environmental challenges from rapid industrialisation, but initiated early discussions on pollution control, leading to regulatory developments such as the 1964 Air Pollution Act (Uekoetter, 2017). East DEU faced more severe environmental degradation, particularly from extensive lignite combustion, resulting in significant air and water pollution with minimal regulatory response. DEU's overall CO_2 emissions, which had fallen to 116 Mt by 1945 (82% below 1939 levels), regained prewar levels by 1954 and reached 814 Mt by 1960 (25% above 1939 prewar levels), reflecting both recovery from wartime destruction and subsequent industrial growth. However, emissions patterns diverged between East and West, with East DEU maintaining higher carbon intensity per unit of economic output. While both states significantly increased their material and energy throughput by 1960, West DEU's greater economic success eventually provided resources for environmental awareness and regulation, whereas East DEU continued to prioritise industrial output at substantial environmental cost (Radkau, 2008).

The DEU case demonstrates WWII's role as a catastrophic, yet pivotal, metabolic reset, effectively clearing the slate for profound restructuring along distinct political-economic pathways. This example illustrates how external political forces –

specifically occupation policies and Cold War division – can reshape postwar socio-metabolic trajectories fundamentally even when starting with similar wartime circumstances. The divergent paths of East and West DEU reveal that institutional arrangements often prove more decisive for long-term resource flow patterns than physical starting conditions.

Despite sharing the same wartime devastation and similar industrial traditions, the two German states developed starkly different socio-metabolic profiles based on their contrasting economic systems and international alignments. This natural experiment demonstrates the critical role of governance structures in mediating how societies rebuild their material and energy relationships following major disruptions.

3.2.4 Italy (ITA)

ITA's socio-metabolic transition during the 1935–1960 period traced a transformative journey marked by structural shifts from fascist autarky through wartime devastation to the remarkable postwar 'economic miracle'. Four distinct phases delineated this evolution: fascist industrial development (1935–1940); wartime disruption (1940–1945); challenging recovery (1945–1950); and accelerated growth and restructuring (1950–1960).

Under Mussolini's regime (1935–1940), ITA pursued autarky with targeted industrial growth aimed at reducing foreign dependency. This policy led to a modest metabolic expansion, evidenced by cement production increasing from 4 Mt in 1935 to 5 Mt by 1939 (a 25% rise) and electricity generation increasing 31%. Despite these gains, ITA's economy remained constrained by resource scarcity, negligible domestic oil production, declining coal output, and continued dependence on imported coal from DEU and GBR (Petri, 2002; Zamagni, 1997).

WWII drastically reshaped ITA's socio-metabolic trajectory, particularly from 1943 onwards. Allied invasions and the German retreat inflicted devastating damage on infrastructure, transportation networks, and key industries. Steel production plummeted from 2 Mt in 1939 to merely 0.2 Mt by 1943 (a 92% decline), while cement production collapsed to 1 Mt, marking an 80% reduction. Severe disruptions in energy supplies exacerbated this crisis further, with coal output decreasing sharply to just 1 Mt by 1944, which was 65% below 1939 levels. Overall industrial output by 1945 had fallen to approximately 20% of prewar productivity, accompanied by profound societal impacts, including approximately 450,000 deaths and widespread population displacement (Castronovo, 2013).

The immediate postwar period (1945–1950) was characterised by a slow and challenging recovery due to extensive infrastructure damage and political instability. However, significant international assistance via the Marshall Plan (1948–1952), with a total investment of roughly $1.5 billion, proved pivotal, funding critical imports of coal, oil, machinery, and technology, thereby enabling rapid industrial reconstruction and currency stabilisation (Harper, 1987). Moreover, domestic reforms under the De Gasperi government and strategic state-led interventions through institutions such as the Institute for Industrial Reconstruction (IRI) – which managed vital sectors such as steel, automobiles, cement, and energy – facilitated efficient rebuilding efforts (Amatori, 2011). ITA's early involvement as a founding member of the ECSC (1951) secured reliable resource access and encouraged an export-oriented industrial expansion (Ranieri, 1984).

The 1950s marked ITA's true socio-metabolic transformation, widely recognised as 'Il Miracolo Economico'. Crucially, ITA's energy landscape evolved significantly, marked by a substantial shift towards petroleum, driven by inexpensive Middle Eastern imports that accounted for 35–40% of primary energy by 1960. ITA's domestic coal production, which had never been substantial (2.6 Mt in 1939), declined further during and after the war and did not regain its prewar level, falling to just 1.0 Mt by 1960 (63% below 1939 levels). The postwar period also saw substantial growth in oil production, which regained its 1939 level by 1951 and grew from negligible levels to about 2 Mt by 1960, contributing to ITA's diversification away from coal dependency. Furthermore, the rise of indigenous natural gas production – from zero before 1946 to 69 TWh by 1960, primarily from the Po Valley – notably boosted northern ITA's industrial competitiveness, facilitating reduced reliance on coal (Pozzi, 2009). This decade witnessed extraordinary growth across all major sectors. By 1960, steel production, which had collapsed to 0.2 Mt in 1943 (92% below 1939 levels), regained its prewar level by 1949 and soared to 9 Mt (300% above 1939 prewar levels). Cement output, which fell to 1 Mt in 1943 (80% below 1939 levels), regained prewar levels by 1947 and reached 18 Mt by 1960 (259% above 1939 levels). Electricity generation, which declined to 13 TWh in 1945 (30% below 1939 levels), regained prewar levels by 1947 and reached 54 TWh by 1960 (200% above 1939 levels). This metabolic and industrial surge was supported by extensive infrastructural developments in transportation networks (motorways, railways, and ports), public housing, and rapid electrification. This was complemented by significant internal migration, predominantly from southern regions to burgeoning industrial centres in the north, providing a critical labour force for expanding industries (Colitti, 1979; Foot, 2020; Ginsborg, 2006).

By 1960, ITA's economy had transitioned from a resource-constrained, semi-peripheral one to an emergent industrial powerhouse with heightened material prosperity. The GDP per capita, which had fallen to $2,831 during the war (46% below 1939 levels), regained its prewar level by 1950 and reached $9,430 by 1960 (80% above 1939 prewar levels), and societal standards of living improved considerably, evident in the widespread adoption of consumer durables (Ciocca, 2003). Nevertheless, this transformation came at a substantial environmental cost: intensified fossil fuel dependence; unregulated air pollution concentrated in northern industrial hubs; and dramatically increased CO_2 emissions, which had fallen to just 3.6 Mt in 1944 (92% below 1939 levels), regained prewar levels by 1951, and rose to approximately 109 Mt by 1960 (137% above 1939 prewar levels).

ITA's experience illustrates how wartime devastation can function as a catalyst for an accelerated socio-metabolic transition when combined with supportive institutional arrangements and external capital flows. The Italian case demonstrates the 'advantages of the reconstruction' phenomenon, in which the opportunity to rebuild damaged infrastructure using more modern technologies enables rapid advancements beyond prewar capabilities. This process was facilitated further by institutional innovations and international integration that created stability for long-term investments and resource access arrangements.

3.2.5 Japan (JPN)

During the 1935–1960 period, JPN experienced an extraordinary socio-metabolic transformation characterised by imperial militarisation, catastrophic wartime collapse, US-led occupation, and rapid postwar industrial revival. This transformation unfolded through four distinct phases: wartime mobilisation (1935–1941); wartime decline (1941–1945); occupation and initial recovery (1945–1950); and rapid economic growth (1950–1960).

Prewar JPN's metabolism focused on military-industrial expansion driven by imperial ambitions. Between 1935 and 1940, JPN significantly boosted its industrial output, exemplified by its steel production increasing from 4.7 Mt to 6.9 Mt (a 46% rise) and cement production growing from 5.5 Mt to 6 Mt (a 10% rise). Despite territorial expansion into Manchuria, Korea, and parts of CHN, JPN remained severely constrained by inadequate domestic energy resources, particularly petroleum, compelling further military aggression in resource-rich Southeast Asia (Barnhart, 1987; Lockwood, 1954).

WWII dramatically disrupted JPN's metabolic trajectory. The naval blockade and the conventional firebombing of more than sixty cities progressively strangled Japan's industrial economy, severing it from imported raw materials and destroying its urban production centres; the atomic bombings of Hiroshima and Nagasaki in 1945 then marked the final, symbolic point of a near-total industrial and societal collapse (Goetz, 1996; United States Strategic Bombing Survey, 1946). Industrial production plummeted drastically, with steel production falling by 70%, cement by 80%, and coal by 40% from prewar levels. Severe shortages in fuels, raw materials, and labour crippled JPN's industrial capacity, causing an almost complete halt to steel production by 1945 (Johnson, 1982).

Ironically, the nation's catastrophic collapse during WWII laid the groundwork for a subsequent metabolic renaissance. The immediate postwar occupation period under the Supreme Commander for the Allied Powers (SCAP, 1945–1952) initially focused on meeting basic needs and demilitarisation (Dower, 1999; Schaller, 1988). However, the USA-led occupation soon shifted towards economic revival amid escalating Cold War tensions. Land reforms dissolved feudal estates, enhancing agricultural productivity, thereby supporting population recovery and urban migration (Schonberger, 2012). Although the occupation authorities initially targeted the powerful *zaibatsu* conglomerates for dissolution, many reemerged later as highly efficient *keiretsu*, which were instrumental in JPN's subsequent economic surge (Hadley, 1970; Morikawa, 1992). The Dodge Plan (1949) stabilised JPN's economy, addressing rampant inflation and creating the foundation for sustainable economic growth (Kōsai, 1986).

The outbreak of the Korean War (1950–1953) was pivotal, turning JPN into a key supply base for UN forces. This external stimulus catalysed JPN's economic revival, fuelling investments in modern equipment, USA surplus technology, and the redevelopment of critical infrastructure (ports, railways, and electric grids) (Yasuzo, 2007). Consequently, JPN's industrial output rapidly recovered, surpassing prewar levels by the early 1950s. The Priority Production Program explicitly channelled scarce resources such as coal and steel into strategic industries, enabling rapid economic reconstruction (Yamamura, 2022).

By the mid-1950s, JPN entered a period of unprecedented growth, becoming an industrial powerhouse by 1960. Steel production, which had collapsed to 2.1 Mt by 1945 (69% below 1939 levels), regained its prewar level by 1952 and surged to 28.3 Mt by 1960 (322% above 1939 prewar levels). Cement output, which fell to 1.2 Mt in 1945 (80% below 1939 levels), regained prewar levels by 1951 and reached 25 Mt by 1960 (312% above 1939 levels). Electricity generation, which declined to 22 TWh in 1945

(36% below 1939 levels), regained prewar levels by 1948 and grew to 115 TWh by 1960 (238% above 1939 levels).

Krausmann et al. (2011) found that JPN's material consumption increased nearly fivefold between 1945 and 1970, with the most dramatic acceleration occurring in the 1950s. This represented one of the most rapid socio-metabolic transitions in modern history, with per capita material use rising from below 3 tons during the immediate postwar period to over 10 tons by the early 1960s.

JPN's energy transition was particularly notable, as oil rapidly replaced coal as the dominant energy source. By 1960, oil comprised roughly 35% of JPN's primary energy consumption, facilitated by inexpensive Middle Eastern crude oil imports (Hein, 1990). JPN's coal production, which had fallen 40% below its 1939 level during the war, recovered gradually and barely regained its prewar level by 1957, reaching 49 Mt by 1960 (just 1% above 1939 levels) – reflecting the structural shift towards imported petroleum rather than domestic coal expansion. Domestic coal mining was restored and even expanded, but oil's superior convenience and efficiency drove rapid infrastructure development, including refineries and petrochemical plants (Yonekura, 1994). Furthermore, hydroelectric power projects, notably the Kurobe Dam, diversified JPN's energy mix further (Komiya et al., 1988). Electricity generation regained its 1939 level by 1948 and expanded 238% above prewar levels by 1960. Industrial diversification marked JPN's emergence on the global stage, with substantial growth in textiles, automobile manufacturing, shipbuilding (soon becoming the world's leading shipbuilder), machinery, and electronics (Uriu, 1996). JPN adopted cutting-edge, energy-efficient technologies and innovative organisational structures, distinguishing its metabolic profile through exceptional resource efficiency and substantial import dependency (Maddison, 2003). Krausmann et al. (2011) highlighted how JPN achieved remarkably high resource productivity during this period compared to other industrialising nations, setting patterns that would later characterise its development model (Krausmann et al., 2011).

This rapid industrialisation posed notable demographic implications. Despite wartime losses, JPN's population grew significantly, from approximately 67 million in 1935 to 94 million by 1960 due to postwar baby booms and repatriation efforts (Watt, 2009). Urban migration intensified, fundamentally altering JPN's social and spatial structure, facilitating industrial labour availability, and increasing domestic resource demands (Shimizu, 2017). However, this explosive growth was not without significant environmental consequences. JPN's CO_2 emissions, which had fallen to 77 Mt in 1945 (40% below 1939 levels), regained prewar levels by 1952 and reached 232 Mt by 1960 (82% above 1939 prewar levels), reflecting postwar industrial expansion and the shift towards fossil fuel-intensive production. Severe pollution problems began emerging in the late 1950s, exemplified by the Minamata mercury poisoning disaster (1956) and worsening air pollution in industrial hubs such as Kawasaki and Yokkaichi (George, 2002). Although environmental regulation was minimal at this time, these issues foreshadowed future environmental policy interventions (Broadbent, 1998).

The Japanese case provides perhaps the clearest example of how wartime destruction paradoxically can accelerate a socio-metabolic transition by enabling comprehensive rebuilding with more advanced technologies and institutional arrangements. JPN's remarkable recovery and transition – driven by a combination of strategic external aid, innovative domestic policies, resource efficiency imperatives, and resilient societal effort

– established the foundation for its emergence as a global economic powerhouse in subsequent decades.

3.2.6 The Soviet Union (USSR)

During the 1935–1960 period, the USSR underwent a profound socio-metabolic transition characterised by dramatic shifts, severe disruptions, and extraordinary industrial expansion under a centrally planned economy. This transformative period is divided into four main phases: prewar Stalinist industrialisation (1935–1941); the Great Patriotic War (1941–1945); postwar recovery (1945–1950); and accelerated industrial growth (1950–1960).

During the prewar Stalinist phase, the USSR rapidly industrialised with aggressive central planning – prioritising heavy industry, military production, and infrastructure – though often at the expense of efficiency, consumer welfare, and environmental considerations. Steel production increased significantly, from 13 Mt in 1935 to 19 Mt by 1939 (a 46% increase), and coal production grew from 84 Mt to 111 Mt (32% growth) simultaneously. Although the industrial output rose markedly, the economy remained energy-intensive and inefficient, driven by quantity-focused production targets (Allen, 2009; Hunter, 2014).

Material flow accounting studies by Krausmann et al. (2016a) indicated that the USSR's domestic material consumption reached approximately 5–6 tons per capita by 1940, significantly below Western industrial economies despite the rapid industrialisation, reflecting the USSR metabolic regime's transitional nature at the time (Krausmann et al., 2016a).

WWII, beginning with the German invasion in 1941, severely disrupted the USSR's metabolism, leading to catastrophic human and material losses. An estimated 20–27 million USSR citizens died during the war, roughly 14% of the prewar population, and entire western regions were devastated (Ellman and Maksudov, 1994). Industrial output initially collapsed: coal production fell to 74 Mt in 1942, a 41% decline from 1940 levels. However, the wartime economy rapidly adapted through a remarkable evacuation of more than 1,500 factories in eastern regions, primarily to the Urals and Siberia (Manley, 2013). By 1943, despite severe hardships and resource constraints, the USSR surpassed DEU in producing tanks and aircraft, demonstrating an extraordinary mobilisation capability (Mawdsley, 2005; Overy, 1998).

Postwar recovery, governed by the Fourth Five-Year Plan (1946–1950), emphasised restoring heavy industry and infrastructure without substantial external aid, relying instead on internal resources, reparations extracted from occupied Eastern European countries, and forced labour from the gulag system (Filtzer, 2007). By 1950, production levels exceeded prewar benchmarks: steel reached 28 Mt (44% above 1940 levels); coal reached 182 Mt (a 45% increase); and electricity generation reached 91 TWh (an 89% increase).

The 1950–1960 period saw exceptional growth, as the USSR's industrial output soared, reflecting both substantial industrial achievements and the continued prioritisation of heavy industry, though official statistics should be interpreted with caution given known reporting biases in centrally planned systems. Coal production, which declined to 74 Mt in 1942 (40% below 1940), regained prewar levels by 1947, reached 360 Mt by 1960 despite the wartime devastation of key mining regions. Oil production fell during the war, but recovered robustly after the war and regained prewar levels by 1949, growing by 580% from 1945 levels to 148 Mt by 1960. Notably, the USSR's energy mix diversified significantly, shifting from a predominantly coal-based system before the war to a broader reliance on oil and emerging use of natural gas by 1960 (Campbell, 1968; Dienes and Shabad, 1979). The Volga-Ural oil fields became central to energy strategies, enabling the USSR to become a net oil exporter by the late 1950s, enhancing its geopolitical standing and economic strength (Considine and Kerr, 2002). Gas production during the 1935–1960 period also experienced significant growth (a 2,500% increase). Electricity generation, which fell 25% below its 1940 level during the war, regained prewar levels by 1946 and reached 290 TWh by 1960 (505% above 1940 prewar levels), driven by massive hydroelectric and thermal power plant construction, with electricity generation more than quadrupling between 1940 and 1960. Extensive infrastructure projects, urban rebuilding, and new industrial centres resulted in significant increases in heavy material use, particularly cement, by 1960. Steel production surged to approximately 70 Mt by 1960 – about 270% above 1940 levels – while coal production nearly doubled to 360 Mt. Socio-metabolic analyses by Krausmann et al. (2016a) have indicated that USSR domestic material consumption more than doubled between 1950 and 1960, reaching approximately 12–13 tons per capita, with fossil fuels increasing from approximately 40% to over 50% of direct material input (Krausmann et al., 2016a). By 1960, the USSR had transformed dramatically, emerging as a global industrial power and the second-largest economy worldwide in gross output, symbolised by accomplishments such as launching the Sputnik satellite in 1957. The USSR's GDP per capita, regained its prewar level by 1948 and doubled from a postwar low in 1946 to $6,288 by 1960, thereby demonstrating its industrialisation and central planning impacts (Nove, 1992). This growth partly reflected postwar reconstruction efforts and accelerated industrial expansion under central planning. Wartime devastation had prompted massive mobilisation of labour and resources, which continued into peacetime, fuelling economic growth (Harrison, 1998). However, these economic triumphs came at substantial human, social, and environmental costs, with systemic inefficiencies and a pronounced neglect of sustainability, setting the stage for future economic and ecological challenges. The resource-intensive USSR metabolism resulted in significant environmental degradation, including severe pollution in industrial cities; ecosystem strain from large-scale agricultural expansions, such as Khrushchev's Virgin Lands campaign; and disruptive impacts from massive engineering projects (Feshbach and Friendly, 1992; Goldman, 1972). The USSR's CO_2 emissions, driven by continued heavy coal use and increasing oil consumption, grew substantially, reaching 1,500 Mt by 1960, marking a 260% increase from pre-war levels. These emissions reflected a growth model that prioritised industrial output over sustainability, reinforcing long-term ecological damage.

WWII's role in this metabolic transition was pivotal through three specific mechanisms. First, the war necessitated the mass evacuation of industrial capacity eastward, permanently altering the USSR's economic geography and creating new industrial centres in previously underdeveloped regions (Lewin, 1985; Samuelson, 2011). Second, the German invasion's brutality reinforced the USSR government's determination to attain overwhelming industrial and military capacity, intensifying the prewar emphasis on heavy industry at the expense of consumer goods and environmental considerations (Hanson, 2014; Kotkin, 1997). Third, the war experience validated central planning approaches and state direction of the economy, strengthening institutional arrangements that would shape USSR resource flows for decades (Gregory, 2004).

The USSR case demonstrates how wartime existential threats can intensify pre-existing development trajectories, rather than fundamentally redirecting them. Unlike Western European countries that experienced postwar institutional transformations, the USSR reinforced and accelerated its existing centrally planned industrial model. This path dependency created extraordinary industrial growth, but also locked in resource-intensive development patterns that would prove difficult to modify in subsequent decades. Material flow studies have identified this postwar USSR model as a distinct metabolic regime characterised by uniquely high resource intensity and low efficiency, a direct legacy of wartime mobilisation patterns.

3.2.7 United Kingdom (GBR)

GBR's socio-metabolic transition between 1935 and 1960 epitomises the complexities of an established industrial power navigating war-induced mobilisation, postwar economic restructuring, imperial decline, and modernisation. This period encompassed four distinct, yet interconnected, phases: prewar adjustment (1935–1939); wartime mobilisation (1939–1945); postwar austerity and early recovery (1945–1950); and moderate growth with economic restructuring (1950–1960).

Entering WWII in 1939 as the world's pioneering industrial nation and imperial giant, GBR already had developed a mature industrial metabolism. This maturity was evident in extensive coal production (190 Mt in 1935), significant steel output (10 Mt), and an advanced electricity infrastructure (18 TWh). Prewar industrial growth was modest relative to emerging industrial nations, with steel production rising by 34% (13 Mt by 1939) and electricity generation increasing 47% (28 TWh by 1939) from 1935. Schandl and Schulz's (2002) long-term material flow analyses documented that GBR had already reached a relatively stable metabolic profile by the 1930s, with a domestic material consumption of approximately 10–11 tons per capita, dominated by coal extraction and use (Schandl and Schulz, 2002).

WWII's onset significantly intensified GBR's metabolic flows. Despite severe damage from German bombings (the Blitz) and resource constraints, steel production was sustained near prewar levels, reaching 13 Mt by 1943, while electricity generation surged to 40 TWh by 1944 (a 43% increase from 1939 levels). The war metabolism prioritised military output, particularly armaments and aircraft production, severely restricting civilian consumption through rigorous rationing (Edgerton, 2011; Zweiniger-Bargielowska, 2002). As Krausmann et al. (2008b) noted in their socio-ecological transition analysis, the GBR's domestic material consumption temporarily declined during the war years due to import restrictions and rationing, with significant restructuring of material use towards wartime production. GBR's electricity generation and GDP per capita never fell below their 1939 levels throughout the war, reflecting the sustained intensity of the wartime command economy. WWII's impact profoundly shaped GBR's economic trajectory. Extensive urban destruction, substantial human loss (~450,000 fatalities), and massive financial debts left GBR economically strained, yet ripe for restructuring by 1945 (Barnett, 2011; Calder, 1992). The immediate postwar years were characterised by austerity, as GBR faced economic hardships, loss of export markets, and imperial contraction marked by India's independence in 1947 (Cairncross, 2002). Resource scarcity continued to drive rationing of food and fuel into the late 1940s, ensuring efficient resource allocation (Zweiniger-Bargielowska, 2002).

Schandl and Schulz (2002) found that GBR's domestic material consumption remained below prewar levels until about 1950, reflecting these austere conditions.

The postwar socio-metabolic transition was driven by domestic policies and international support. The Labour government (1945–1951) initiated sweeping reforms, including nationalising key industries such as coal (1947), electricity (1948), and steel (1949), and establishing the National Health Service (1948) and welfare programmes (Morgan, 1985). These moves aimed to modernise industrial sectors, improve working conditions, and support overall societal recovery. Furthermore, the USA-funded Marshall Plan played a crucial role in financing imports of food and raw materials which were vital for reconstruction (Milward, 1984).

GBR's metabolic patterns experienced notable postwar shifts. Coal initially struggled due to the antiquated infrastructure, exemplified by the 1947 coal crisis, which led to electricity shortages (Hausman, 1987). Coal production fell to 165 Mt by 1960, affected by both WWII disruptions and the beginning of a transition to other energy sources. Subsequent mechanisation and management reforms under the National Coal Board stabilised the coal output. The 1950s marked a significant energy transition: Imported Middle Eastern oil became increasingly prominent, growing from under 5% of the energy mix in 1938 to approximately 20–25% by 1960 (Chick, 2007; Katzenstein, 1986). This shift was driven by economic efficiency and policy incentives aimed at reducing urban pollution.

Electricity generation rapidly expanded after the war, driven by increased domestic electrification and industrial demands. Electricity generation, which had been maintained above prewar levels throughout the war, reached 137 TWh by 1960 (395% above 1939 prewar levels). The Electricity Act (1947) significantly expanded the electrical grid, boosting coal consumption initially, but later supporting diversification towards oil and eventually nuclear energy (Chick, 2002; Millward, 2008). The world's first commercial nuclear power station, Calder Hall (1956), symbolised GBR's innovation efforts, although the nuclear energy contribution remained small by 1960 (Williams, 2019). Materials production also rebounded robustly. Steel production reached approximately 22 Mt by 1960, a 67% increase from prewar levels, while cement output which had fallen to 4 Mt by 1945 (50% below 1939 levels), regained prewar levels by 1948 and reached 14 Mt by 1960 (70% above 1939 levels), reflecting extensive infrastructure reconstruction, urban rebuilding, and housing construction. Schandl and Schulz (2002) found, through material flow accounting, that construction minerals nearly doubled as a share of total material consumption between 1945 and 1960, reflecting postwar rebuilding efforts. Additionally, the material productivity (GDP per unit of materials used) increased by approximately 25% between 1945 and 1960, reflecting efficiency improvements in the nationalised industrial sectors (Krausmann et al., 2008b). The automobile industry notably flourished, turning GBR into a leading global car producer by 1960 (Church, 1995). Population growth was modest (~8% increase), but internal migration, urbanisation, and suburban expansion reshaped demographic patterns (Allen and Hicks, 1999).

GBR's postwar economic structure embraced a mixed-economy approach. Following the wartime command economy, the government maintained active intervention, notably through nationalised industries providing essential inputs for the private sector (Middleton, 1996). This period also saw modest GDP per capita growth, reaching $13,800 by 1960 (38% above 1939 levels), indicating steady, but comparatively slower, growth relative to continental Europe's postwar economic boom (Maddison, 2003).

GBR's CO_2 emissions which had declined only modestly during the war (to 418 Mt in 1945, 8% below 1939 levels), regained prewar levels by 1947 and reached 584 Mt by 1960 (30% above 1939 prewar levels). This relatively modest increase compared with other industrial powers reflected GBR's already mature industrial base and the structural decline of coal. Environmental concerns emerged prominently through the 1956 Clean Air Act, enacted in response to the devastating London Smog of 1952 (Brimblecombe, 1989). This pioneering environmental policy fostered metabolic change by encouraging cleaner fuels and establishing smoke control areas, initiating early urban decarbonisation and particulate pollution reduction. While the total CO_2 emissions still increased nationally due to industrial and transportation growth, this marked a significant environmental policy milestone.

Geopolitically, WWII significantly diminished GBR's global standing, increasing its reliance on USA security and imported oil, and accelerating imperial dissolution. This geopolitical repositioning prompted a domestic-focused economic strategy emphasising social welfare, technological innovation, and incremental modernisation (Conekin et al., 1999).

The British case reveals how WWII functioned more as an accelerator of ongoing transitions than a fundamental disruptor for established industrial powers. Unlike continental European nations that experienced institutional transformation through defeat or occupation, GBR's wartime experience reinforced the pre-existing state capacity while accelerating imperial decline. This combination produced a distinctive path of incremental socio-metabolic change characterised by moderate growth, mixed-economy measures, and early environmental policy innovation – a pattern that would shape GBR's development trajectory for decades afterwards.

3.2.8 The USA

The socio-metabolic transition in the USA during the 1935–1960 period vividly illustrates how WWII acted as a crucial accelerator, transforming an economically advanced, but depression-constrained, country into the world's dominant industrial power and consumer society. This transition can be understood in three distinct phases.

In the late 1930s, the USA's economy gradually was recovering from the Great Depression, characterised by idle industrial capacity slowly coming back online. The prewar metabolic recovery was significantly shaped by the New Deal programmes (1933–1938/9), which dramatically expanded the physical infrastructure – constructing or improving over 650,000 miles of roads and 124,000 bridges – as well as energy infrastructure, including major hydroelectric projects such as the Tennessee Valley Authority and Grand Coulee Dam. These investments not only re-activated idle industrial capacity, but also created the physical infrastructure that would prove essential for wartime mobilisation and postwar suburban expansion (Gordon, 2017). Between 1935 and 1939, key indicators such as steel production increased by 38% (from 35 Mt to 48 Mt), and electricity generation rose by 36% (from 119 to 161 TWh), reflecting the economy's initial metabolic recovery. However, this recovery remained incomplete. Gierlinger and Krausmann's (2012) material flow analyses indicated that domestic material consumption had recovered only partially from the Depression, reaching approximately 11 tons per capita by 1939, still below pre-Depression levels. This prewar metabolic profile was dominated by coal, which constituted roughly 40% of direct material input, while construction minerals, reflecting still-depressed building activity, remained at historically low levels.

WWII triggered an extraordinary and unprecedented metabolic mobilisation. The USA, entering the war in late 1941, rapidly evolved into the 'Arsenal of Democracy', exponentially boosting production of ships, aircraft, vehicles, and armaments (Vatter, 1985). Driven by federal interventions such as the War Production Board directives, generous financing mechanisms (war bonds and lend-lease programmes), and strategic infrastructure developments, such as the 'Big Inch' pipeline for efficient oil transport, the economy saw massive industrial scaling (Rockoff, 2012). According to Gierlinger and Krausmann (2012), wartime mobilisation temporarily pushed domestic material consumption to over 15 tons per capita by 1944, primarily driven by increases in fossil fuel and metal ore extraction. Steel production soared to 81 Mt by 1944 (a 70% increase from 1939 levels), electricity generation reached 280 TWh (73% above 1939 levels), and crude oil production rose significantly, from about 182 Mt in 1940 to over 230 Mt by 1945, enabling the USA to supply approximately 60% of Allied oil consumption during the war. At its wartime peak, the USA produced 60% of the world's crude oil, securing a decisive strategic advantage (Yergin, 2008).

The war exerted transformative effects on America's society and economy beyond production statistics. It definitively ended unemployment through mobilisation of millions of men into military service and integration of women into the workforce (the 'Rosie the Riveter' phenomenon) (Goldin, 1991). Wartime policies such as rationing and resource conservation were critical in allocating essential materials to military use, while technological innovations developed during the war (radar, nuclear energy, synthetic rubber) laid foundations for future civilian applications (Higgs, 2006).

Unique among wartime belligerents, the USA emerged from WWII not only undamaged domestically, but also with greatly enhanced industrial capacity and capital accumulation. By 1945, American industrial output had doubled from its 1938 levels across many sectors (Milward, 1980). Although the postwar GDP per capita briefly dipped due to reductions in military spending, the economy quickly transitioned into a prolonged period of unprecedented growth and prosperity (Rostow, 1990). This transition was facilitated by institutional innovations established during wartime, now redirected towards civilian consumption and international economic leadership.

During the 1945–1960 period, America experienced a substantial economic boom, vastly exceeding prewar production figures: steel output reached 89 Mt (86% above 1939 levels); cement production climbed to 57 Mt (153% above 1939 levels); and electricity generation surged to 844 TWh (423% above 1939 levels). This productive expansion supported a fundamental shift towards consumer-oriented production, enabled by specific policies and institutional arrangements with direct wartime origins. Government initiatives such as the GI Bill facilitated suburban housing expansion and educational opportunities, while federal highway funding (culminating in the 1956 Federal-Aid Highway Act) created transportation infrastructure that reshaped settlement patterns and promoted high per capita resource consumption (Margo, 1992).

This postwar transformation represented a comprehensive socio-metabolic transition. Gierlinger and Krausmann (2012) found that the USA's domestic material consumption reached approximately 20 tons per capita by 1960 – the highest in the world – with particularly dramatic increases in construction minerals, reflecting the massive suburban housing and highway construction booms. This represented nearly a doubling of per capita material consumption in just 15 years after the war, an unprecedented metabolic acceleration. This extraordinary acceleration was driven primarily by two material categories: construction minerals (reflecting the massive suburban housing and highway construction boom) and fossil fuels (supporting unprecedented personal mobility and energy-intensive consumer lifestyles). As a result, the American economy's material composition shifted significantly, with construction minerals increasing from approximately 25% of direct material input in 1940 to nearly 40% by 1960, reflecting the massive infrastructure development during the postwar period.

The postwar American energy system underwent a profound transition, building directly on wartime developments. While coal production declined slightly after peaking in 1944 (down 36% by 1960), oil and natural gas production increased dramatically, highlighting a broader shift away from solid fuels. Oil production reached 348 Mt (a 50% increase from 1945 levels and a 104% increase from 1939 levels). The USA's share in global oil production declined to 33% by 1960 due to faster production growth in other countries, notably the USSR. Natural gas production surged dramatically, to approximately 4,000 TWh by 1960, representing a 223% increase above 1945 levels (a 360% increase from 1939 levels), marking a significant energy transition towards gas consumption. This marked a significant energy transition towards petroleum dependency, reinforced by the rapidly growing automobile culture and suburban development patterns that emerged directly from wartime technological and organisational innovations (Nye, 1998).

This emerging metabolic profile established an affluent, consumption-centric society unlike any previously seen. However, the transition also elicited environmental stresses, notably air pollution and resource extraction impacts. Urban smog, particularly severe in Los Angeles due to automobile emissions and heavy industry, led to early research into air quality and tentative legislative actions (e.g., the 1955 Air Pollution Control Act) (McCarthy, 2007). Conservation advocacy persisted, though the dominant economic trajectory prioritised growth and fossil fuel dependency (Hays, 1989).

By 1960, the USA had solidified its distinctive metabolic profile, marked by high per capita GDP ($18,000, 62% above 1939 levels) and significantly increased CO_2 emissions (2,900 Mt, 73% above prewar levels), establishing the world's highest per capita emissions rate. Fischer-Kowalski and Haberl (2007) found that the US model of industrial metabolism, characterised by resource use, was approximately 5–10 times higher than pre-industrial societies, with energy consumption dominated by fossil fuels. Unlike European countries and JPN, which developed more resource-efficient metabolic profiles during postwar reconstruction, the US model emphasised abundance over efficiency, establishing consumption patterns that would be emulated globally later.

WWII's pivotal role in this transformation went beyond merely accelerating existing trends. The war fundamentally restructured institutional arrangements, technological capabilities, and social expectations about consumption and resource use. It also legitimised federal economic coordination; established new relationships between government, industry, and science; and created both a physical infrastructure and cultural expectations that shaped subsequent development patterns. These war-induced changes collectively established a high-throughput metabolic regime that would serve as a model for development globally in subsequent decades, with profound implications for resource flows and environmental impacts worldwide.

Table 1 presents a comparative summary of the eight nations.

Table 1 Comparative summary table

Country	*Socio-metabolic transition*	*Metabolic transition drivers*	*Key metabolic patterns*	*Consequences*	*Key policies/mechanisms*	*Resource profile*	*Role of WWII in metabolic transition*
CHN	Agrarian to early industrial; disrupted by war; state-driven industrialisation post-1949	WWII devastation, Civil War, Communist central planning, Soviet aid, Great Leap Forward (which disrupted metabolic patterns despite industrialisation goals)	Low baseline; collapse in war; post-1949 rapid coal and steel expansion, famine (GLF)	Uneven industrialisation; severe famine during GLF disrupted metabolic development, rising pollution; eventual long-term takeoff	Five-Year Plans, Soviet assistance, Great Leap Forward (1958), state-owned industries	Coal-based industrialisation; low oil use pre-1960; heavy reliance on state-driven extraction	Severe destruction set stage for Communist-led industrialisation; war forced reorganisation
FRA	Industrial but stagnating pre-war; post-war reconstruction and modernisation via Monnet Plan	WWII destruction, Monnet Plan, Marshall Plan aid, European integration (ECSC)	Pre-war stagnation, wartime collapse; post-war rapid growth in steel, energy, infrastructure	Industrial modernisation, urban expansion, state-led growth; initial environmental strain	Monnet Plan, Marshall Plan aid, nationalisation of key industries, European integration	Coal primary until 1950s, oil increasing; steel, cement production surged in 1950s	Occupation and destruction led to centralised modernisation drive; ECSC integration pivotal
ITA	Pre-war partial industrialisation; post-war rapid industrial expansion and economic miracle	WWII destruction, Marshall Plan aid, export-led growth, state-led industrial investment	Wartime contraction; post-war catch-up growth in industry, infrastructure, energy consumption	Rapid urbanisation; consumer society emergence; regional economic divide (North-South)	Marshall Plan, industrial subsidies, state investments (IRI), trade liberalisation	Limited domestic resources; transition from coal to oil; large-scale steel/cement imports	War damage erased outdated structures; Marshall Plan allowed rapid modernisation
DEU	Pre-war industrial giant; post-war devastation and reindustrialisation (Wirtschaftswunder)	WWII destruction, Marshall Plan aid, currency reform, labour force mobilisation	Collapse during war; 1950s boom (steel, energy, construction); rapid productivity rise	High industrial output; Cold War-driven technological advancement; environmental neglect	Marshall Plan, Social Market Economy, export-led growth, currency stabilisation	Coal-heavy economy; post-war resource imports; steel boom through ECSC integration	Severe disruption; rebuilding with new technology created a highly efficient industry
USSR	Command economy with forced industrialisation; war destruction followed by heavy industry push	WWII destruction, central planning, Cold War military buildup, resource mobilisation	Pre-war heavy industry focus; war impact; post-war military-industrial expansion	Militarised economy; strong industrial base but poor consumer sector; inefficient metabolism	Central Planning, Five-Year Plans, state control of heavy industry, Cold War arms race	Coal-dominant; oil expansion later; inefficient but vast industrial throughput	Extensive destruction; post-war heavy-industry expansion intensified an existing trajectory
USA	Steady industrial leader; wartime expansion followed by consumer boom and infrastructure growth	WWII military mobilisation, Cold War economic expansion, domestic consumption boom	Wartime peak; post-war steady rise in oil, consumer goods, highway infrastructure	Dominance in global economy; suburbanisation; early local environmental awareness (smog laws)	New Deal policies, military Keynesianism, Marshall Plan (as giver), infrastructure boom	Oil-fuelled expansion; domestic coal decline; infrastructure boom raised steel/cement demand	Stimulated industrial production; post-war pivot to consumer expansion and infrastructure
JPN	Pre-war industrialising; devastated in war; post-war US-guided reconstruction and rapid expansion	WWII devastation, US occupation reforms, Korean War export stimulus, MITI guidance	Wartime collapse; post-war rapid growth (steel, energy, cement) via export-led policies	High-tech industry expansion; leading efficiency in industrial metabolism; urban growth	MITI industrial policy, US aid, Zaibatsu reforms, export-driven strategy	Resource-poor; heavily import-dependent; energy-efficient manufacturing focus	Near-total destruction enabled US-led reform, making Japan an efficient export-driven power
GBR	Pre-war industrialised; post-war rebuilding with moderate growth; transition to consumer economy	WWII mobilisation, post-war austerity, welfare state expansion, decolonisation impacts	Peak wartime coal and steel; post-war plateau, shift to oil and consumer-driven economy	Moderate industrial expansion; welfare state; early signs of deindustrialisation challenges	Nationalisations (coal, rail, steel), welfare state (NHS 1948), trade reorientation	Coal-reliant pre-war; early shift to oil post-war; declining resource self-sufficiency	War mobilisation and rationing accelerated ongoing transitions rather than causing a sharp break

4 Discussion

4.1 Comparative analysis and synthesis

4.1.1 Resource distribution between Allied and Axis powers

The Allied powers (grouped here by eventual wartime alignment) dominated global oil production during WWII, with their share comprising approximately 71% in 1939 due to increased production from the USA and USSR, while the Axis powers had a minimal share, at about 0.35% in 1939, due to limited production. This stark resource asymmetry directly shaped military capabilities and strategic options, ultimately contributing to the war's outcome.

This resource disparity extended across multiple domains. The dominance of the Allied powers' coal production rose from 65% in 1939 to 78% in 1945, while the Axis Powers' share fell from 19% to 7%. The war led to temporary declines in most countries, but after the war, nations generally recovered or increased their coal production, with the Allies maintaining global dominance. By 1945, the USA and the USSR dominated global gas production, contributing to 94% of the total, while the Axis powers had negligible production. While natural gas remained quantitatively minor compared to coal and oil during the war itself, the wartime expansion of the gas infrastructure – particularly pipeline networks and processing facilities – established the foundation for its rapid postwar growth, when it became a major component of the energy mix in both countries.

During the war, Allied countries underwent a 20% increase in steel production, growing from 73% to 93% of global output, reflecting their industrial superiority during WWII. Conversely, the Axis powers experienced a 75% decline in steel production during the war, with initial increases, but suffering heavy losses due to the war. After the war, both sides demonstrated significant recovery, with the Axis share of global steel dropping from 27% in 1939 to 7% in 1945, underscoring the war's devastating impact on Axis industries and the pivotal role of industrial capacity factored into the Allies' victory. The Allies' share of global cement production fell significantly during WWII, but recovered partially by 1945. The Axis powers experienced a similar decline, with a slight recovery by 1945. Consequently, the Allied powers increased their share of global emissions from 63% to 78% from 1939 to 1945, contrasting with the Axis powers' decrease from 18% to 5%, reflecting the profound impact of WWII on industrial capacities and CO_2 emissions.

These resource imbalances played a decisive role in determining war outcomes, while simultaneously establishing the material foundation for postwar power structures

4.1.2 Common mechanisms across countries

A comparative analysis of the country cases presented in section 3 reveals consistent causal mechanisms linking WWII experiences to subsequent socio-metabolic transformations, although their manifestations varied by national contexts. These mechanisms integrated technological, institutional, and social dimensions of change.

1 Wartime mobilisation and industrial expansion: WWII catalysed unprecedented industrial mobilisation, permanently altering production systems through three pathways: technological innovation; organisational learning; and spatial redistribution. Military necessity drove the development and scaling of production

technologies, thereby shaping postwar resource flows for decades (Edgerton, 2011). Wartime industrial mobilisation established physical infrastructure and organisational capabilities, enabling dramatic postwar accelerations in material and energy flows. Wartime experiences demonstrated the feasibility of coordinating massive production efforts and deliberately redirecting resource flows towards strategic objectives, creating institutional templates that influenced postwar development policies (Higgs, 2006; Koistinen, 2004).

2 Creative destruction and the advantages of reconstruction: WWII's physical devastation paradoxically created opportunities for accelerated transitions in a manner akin to what Schumpeter termed 'creative destruction' (Schumpeter, 1943): the war swept away the entrenched distributional coalitions that Olson (1982) argued produce 'institutional sclerosis' in stable societies, so the most heavily damaged countries could rebuild without those constraints. Countries that experienced severe wartime damage often gained reconstruction advantages by rebuilding with more modern infrastructure and institutions than those with intact, but outdated systems (World Bank, 1998). From a socio-metabolic perspective, this mechanism can be understood through the lens of the stock-flow-service nexus (Haberl et al., 2017). Material stocks accumulated in buildings, infrastructures, and machinery determine ongoing flows of materials and energy, while simultaneously creating path dependencies and lock-in effects through their long lifetimes. WWII's large-scale destruction of these accumulated stocks broke existing lock-ins, creating opportunities for fundamentally different infrastructure configurations, while simultaneously driving massive material and energy requirements for rebuilding. As demonstrated in Section 3, this mechanism explains an apparent paradox: countries experiencing the most severe wartime destruction (DEU, JPN) often achieved the most rapid postwar economic growth and technological modernisation. The war's physical destruction broke existing lock-ins, enabling reconstruction with more advanced socio-technical systems (Allen, 2009; Crafts and Toniolo, 1996). This pattern contrasts with countries like GBR, in which a comparative lack of domestic destruction limited comprehensive modernisation opportunities (Broadberry and Crafts, 1996; Olson, 1982). Destruction alone, however, was not decisive. The pace of reconstruction also depended on retained human capital and the institutional conditions shaping recovery.

3 Capital reallocation and governance innovations: WWII triggered massive capital reallocations through deliberate programmes and structural economic shifts, establishing new governance arrangements and shaping resource flows for decades. The Marshall Plan ($13 billion, equivalent to over $170 billion today) (Inflation Calculator, 2025) and USSR-led reconstruction efforts directly responded to wartime devastation, accelerating recovery while introducing new institutional models (Mee, 1984; Steil, 2013). These capital flows were coupled with governance innovations spanning market, state, and hybrid arrangements. As detailed in section 3's country case studies, these postwar governance arrangements directly shaped resource allocation decisions, investment patterns, and technological diffusion pathways. These institutional arrangements mediated the translation of wartime experiences into specific postwar socio-metabolic patterns, explaining why similar war experiences sometimes produced divergent outcomes (Allen, 2009; Gao, 2001).

4 Technological transfer and diffusion acceleration: military-driven research during WWII led to innovations in nuclear technology, synthetic materials, jet engines, electronics, and transportation systems that subsequently transformed postwar production and consumption patterns (Leslie, 1994; Rhodes, 2012). Military-industrial-academic research complexes established during wartime continued after 1945, accelerating technological diffusion across sectors (Mowery and Rosenberg, 1998).

5 Spatial reorganisation of production and consumption: WWII permanently altered the geographical distribution of production and consumption through destructive and constructive mechanisms. Combat operations, strategic bombing, and deliberate industrial relocation fundamentally restructured the spatial patterns of resource flows, creating new centres of extraction, processing, and consumption (Harrison, 1998; Milward, 1980). The war triggered massive urbanisation and internal migration, altering consumption patterns and infrastructure development. New manufacturing hubs and industrial complexes established during the war – comprising clusters of factories, power generation facilities, and supporting infrastructure – typically continued growing after the war, shaping regional development and resource demands (Glaeser and Kohlhase, 2004).

4.1.3 Divergent pathways shaped by political-economic systems

While common mechanisms operated across countries, WWII's socio-metabolic legacy diverged significantly based on political-economic arrangements that emerged from the war. Our analysis identified three distinct socio-metabolic regimes that emerged from WWII:

1 Market-oriented capitalist reconstruction (USA, West DEU, JPN): these countries embraced market mechanisms while maintaining strategic state direction in key sectors. They achieved high growth rates, steadily increased resource productivity, and gradually paid more attention to environmental impacts (Eichengreen, 2008a; Hall and Soskice, 2001).

2 Mixed-economy/coordinated transformation (GBR, FRA, ITA): these countries adopted more extensive state interventions through nationalisation, planning, and welfare state expansion while maintaining market elements. They experienced moderate growth rates, more gradual energy transitions, and comparably early development of environmental policies.

3 Centrally planned socialist industrialisation (USSR, East DEU, CHN): these countries implemented comprehensive central planning with limited market mechanisms, attaining rapid heavy industrial growth, but often with high resource intensity, limited consumer goods production, and minimal environmental protection.

These divergent pathways emerged from the political settlements that followed WWII, demonstrating how wartime experiences were mediated through different institutional arrangements that elicited varying socio-metabolic patterns. Despite these differences, all pathways helped accelerate global material and energy flows, collectively constituting the Great Acceleration.

4.2 WWII and the Great Acceleration

This review demonstrates that WWII functioned as a decisive critical juncture in global socio-metabolic development – a moment when existing path dependencies were disrupted and new developmental trajectories were established. The war's impact was felt through complex causal pathways, rather than simple correlations, transforming how societies organised their material and energy relationships with the environment. Our analysis reveals three distinct types of war impacts on socio-metabolic transitions:

1 Acceleration effects: for countries such as the USA, WWII primarily accelerated existing industrialisation trajectories by removing Depression-era constraints, mobilising idle capacity, and establishing new institutional capabilities for coordinating large-scale resource flows (Gordon, 2017).

2 Redirection effects: for countries such as FRA and GBR, the war redirected existing industrial development along new institutional pathways, establishing mixed-economy arrangements and welfare state structures that shaped subsequent resource allocation decisions (Crafts and Toniolo, 1996).

3 Reset effects: for countries experiencing the most severe disruptions (DEU, JPN, ITA, and [to some extent] CHN), the war functioned as a comprehensive reset, destroying previous socio-metabolic arrangements and creating conditions for fundamentally new development trajectories (Olson, 1982).

These impact types often manifested concurrently within individual countries, with different mechanisms dominant in specific sectors and regions. The interaction between war-induced disruptions and subsequent institutional innovations explains why WWII's socio-metabolic legacy varied significantly between countries despite common underlying mechanisms.

Furthermore, our analysis demonstrates that WWII directly catalysed what Steffen et al. (2015) termed the 'Great Acceleration', i.e., the exponential increases in socioeconomic activities and Earth system impacts after 1950. By identifying specific causal mechanisms linking wartime disruptions to postwar transformations, we moved beyond correlations to establish how WWII functioned as a critical juncture in global socio-metabolic history:

1 Technological acceleration: wartime R&D compressed innovation timelines in areas such as electronics, materials science, chemicals, and energy technologies (Edgerton, 2011; Mowery and Rosenberg, 1998). These innovations transferred rapidly to civilian sectors after 1945, driving productivity growth and new consumption patterns. Nuclear technology, synthetic materials, jet engines, and radar all moved quickly from military to civilian applications (Leslie, 1994).

2 Institutional capacity building and governance models: wartime mobilisation demonstrated the feasibility of coordinating massive resource allocation through new institutional arrangements (Wilson, 2016). These institutional innovations – from the American military-industrial coordination to USSR planning – carried into peacetime, enabling large-scale infrastructure development and industrial expansion that otherwise might have been organisationally impossible (Koistinen, 2004).

3 Social-psychological transformation and consumption norms: WWII altered social expectations through wartime deprivation and postwar prosperity. The wartime experience normalised rapid technological change, while postwar prosperity created expectations of continuously increasing material consumption (Cohen, 2003). These shifts facilitated public acceptance of accelerating resource use and established consumption-oriented identities that proved resistant to later environmental concerns (Dauvergne, 2010).

4 Global integration of resource systems: the war disrupted previous colonial resource networks while establishing new international arrangements for resource access and circulation (Findlay and O'Rourke, 2007). Postwar institutions like the Bretton Woods system, trade agreements, and military alliances created frameworks for accelerated resource flows across national boundaries, facilitating global-scale industrial expansion. New transportation technologies reduced distance friction in global resource flows, enabling complex global supply chains.

These war-induced mechanisms collectively established conditions for exponential resource flow increases that defined the post-1950 period. Without WWII's disruptive effects and subsequent reconstruction imperatives, such extensive institutional, technological, and social reconfigurations likely would not have aligned so rapidly to enable the Great Acceleration (McNeill and Engelke, 2016; Steffen et al., 2015).

4.3 Implications for contemporary sustainability transitions

WWII's catalytic role in reshaping industrial systems offers insights for navigating contemporary sustainability transitions in the climate change context:

1 Crisis-driven transformation: WWII demonstrated how existential threats can mobilise societies to restructure economic systems at extraordinary speeds. Industrial production patterns were redirected towards strategic priorities through both market and non-market mechanisms, showing that rapid resource reallocation is possible when a crisis is perceived as a matter of survival. Contemporary climate change may, under some conditions, motivate similarly rapid socio-metabolic restructuring when it is framed as an urgent collective challenge requiring broad mobilisation (Delina and Diesendorf, 2013; Delina and Sovacool, 2018; Newell and Paterson, 2010). Recent experiences with rapid policy responses to global crises, such as the COVID-19 pandemic, demonstrate that modern societies retain significant capacity for rapid institutional coordination and resource reallocation when facing perceived existential threats (Boin et al., 2020). At the same time, WWII posed a more immediate and visibly bounded threat than climate change, which unfolds more gradually, unevenly across regions, and without a single identifiable adversary.

2 Path dependencies and strategic choices: infrastructure choices made during postwar reconstruction established enduring path dependencies and carbon lock-in in energy, transportation, and urban systems, as illustrated in the country studies. This historical pattern highlights the critical importance of ensuring that contemporary crisis responses and recovery investments align with long-term decarbonisation goals (Markard et al., 2020). The post-WWII experience reveals how physical reconstruction creates 'windows of opportunity' for system transformation,

suggesting that contemporary disruptions similarly might create opportunities for transformative system change if approached strategically and recovery is deliberately steered in low-carbon directions (Loorbach et al., 2017).

3 Technological transfer and adaptation: wartime innovations successfully transferred to civilian applications through policies and institutional arrangements, as detailed in the country studies. This pattern suggests that contemporary climate innovation might benefit similarly from strategic coordination between public research, private implementation, and appropriate governance frameworks (Mazzucato, 2018; Newell, 2019). However, the socio-metabolic lens reveals that technological innovation alone is insufficient without corresponding institutional and social changes. Post-WWII efficiency improvements were often overwhelmed by scale effects as consumption expanded dramatically (Fischer-Kowalski et al., 2014; Krausmann et al., 2009). This suggests that contemporary sustainability transitions require not only technological innovation, but also new governance arrangements and social practices to address rebound effects (O'Neill et al., 2018; Santarius et al., 2016). This insight is particularly relevant for policy makers designing post-crisis recovery strategies, as infrastructure and institutional choices made during reconstruction periods can establish development trajectories that persist for decades (Jacobs, 2011). Moreover, as Mazzucato (2013) argues, public investment in R&D is critical for invention, but commercialisation also requires private-sector engagement. The post-WWII experience illustrates this public-private nexus: government-funded wartime research generated breakthrough technologies, while their civilian adoption depended on firms such as Krupp and Volkswagen in DEU and the zaibatsu (later reorganised as keiretsu) networks in JPN, which played important roles in both wartime production and postwar reconstruction.

4 Governance innovation: WWII catalysed institutional innovation across multiple levels of governance, from local resource management to international coordination. These new governance arrangements proved essential for coordinating massive investments and structural changes after the war (Ikenberry, 2019; Ruggie, 1982). Contemporary sustainability transitions similarly require governance innovation to manage complex system transformations across sectors and scales (Köhler et al., 2019; Newell, 2019). As Frantzeskaki et al. (2012) argue, governing societal transitions to sustainability demands selective participatory processes of envisioning, negotiating, learning, and experimenting (Frantzeskaki et al., 2012). These ideas resonate with historical wartime and post-war coordination mechanisms, suggesting that governance responses to past crises contain actionable lessons for contemporary sustainability governance. Climate change, like WWII, demands coordinated responses on multiple levels, from local adaptation to global mitigation efforts (Burch et al., 2014; Ostrom, 2010). The governance innovations that emerged from WWII – including new forms of public-private coordination, international cooperation mechanisms, and stakeholder engagement processes – provide important precedents for the institutional arrangements needed to manage contemporary sustainability challenges (Gross and Sampat, 2023). In line with transition management thinking, Kemp et al. (2005) conceptualise sustainability as an adaptive process requiring the integration of technological, institutional, social, and governance dimensions – a finding that resonates with our analysis of WWII-driven

transitions. The experience suggests that crises can catalyse institutional innovation when existing governance arrangements prove inadequate (Sabel and Victor, 2022).

Recent developments further underscore these parallels. The COVID-19 pandemic demonstrated how modern societies can mobilise resources and reshape economic activities rapidly in response to perceived existential threats (Sovacool et al., 2020). Similarly, the Russia-Ukraine war (2022–present) has forced European nations to reconfigure energy systems rapidly, highlighting how geopolitical disruptions can accelerate energy transitions when strategic imperatives align with sustainability goals (Boehm and Wilson, 2023). Even so, these responses have remained largely regional and fragmented rather than globally coordinated.

The recent crises highlight how much more difficult large-scale transition has become in today's more divided geopolitical context, especially compared with the unusually favourable postwar setting. This also suggests that crisis alone is insufficient to drive sustainability transitions; the political and institutional conditions enabling coordinated response are equally decisive.

5 Conclusions

WWII fundamentally reshaped global socio-metabolic systems through complex interactions between technological innovation, institutional transformation, and social change. The war functioned as a critical juncture that disrupted existing path dependencies while establishing new developmental trajectories that would shape resource flows and environmental impacts for decades afterwards. The socio-metabolic lens reveals the profound depth of WWII's legacy, moving beyond conventional economic or political analyses to demonstrate how the war transformed modern societies' material foundations, highlighting the complex interplay between resource availability, economic power, and military might, as well as the consequences of resource scarcity and competition.

Perhaps most significantly, our analysis demonstrates how WWII simultaneously enabled unprecedented material prosperity and created conditions for unprecedented environmental challenges. The institutional arrangements, technological systems, and consumption patterns established during and after the war collectively drove the Great Acceleration in global resource use and environmental impacts, creating the material foundation for contemporary sustainability challenges. These findings have important implications for contemporary policy makers who must design strategies for rapid system transitions while avoiding the environmental and social costs that characterised much of the post-war development trajectory. By understanding the drivers, patterns, and consequences of this historical transition, policymakers, researchers, and stakeholders can gain insights into the complexities involved in large-scale socio-technical transformations. The historical experience of WWII-induced transitions reveals both the possibility of rapid system change in response to perceived existential threats and the dangers of establishing new path dependencies that may prove problematic in the longer term.

As societies navigate contemporary sustainability transitions, this historical perspective offers both inspiration and caution – demonstrating the human capacity for extraordinary mobilisation and transformation while highlighting the importance of directing such transformations towards environmentally sustainable and socially equitable outcomes, rather than merely accelerating material throughput. The post-WWII experience suggests that major crises can create opportunities for transformative change, but that the direction and quality of that change depend on governance arrangements, technological choices, and social priorities that shape response and reconstruction efforts. The governance innovations and coordination mechanisms developed during WWII provide valuable precedents for the institutional arrangements needed to manage contemporary sustainability transitions, while the environmental costs of post-war development offer important cautionary lessons for ensuring that rapid transformation contributes to, rather than undermines, long-term sustainability objectives.

This study has several limitations, suggesting directions for future research. The socio-metabolic transition framework could be applied to conduct deeper sectoral analyses (e.g., agriculture, transportation, housing) which would reveal additional mechanisms through which wartime disruptions have shaped long-term resource flows. Such sector-specific investigations could provide a more nuanced understanding of how war-induced changes affected particular domains of social and economic life, potentially revealing path dependencies not visible at the aggregate level. The framework could also be extended productively to analyse other major historical disruptions – such as economic crises, pandemics, or regional conflicts – to assess how different types of systemic shocks shape the social metabolism. A further limitation is the insufficient attention to the public-private nexus in war-induced transitions. The specific mechanisms through which public-private coordination shaped socio-metabolic transitions across capitalist, mixed, and centrally planned systems represent an important area for future research. These future research directions are particularly important for policy makers who need empirical evidence about which governance mechanisms and institutional arrangements are most effective for managing different types of sustainability transitions under varying conditions.

Appendices/Supplementary materials are available on request by emailing the corresponding author.

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Declarations

All authors declare that they have no conflicts of interest.

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