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# Deep transitions: Theorizing the long-term patterns of socio-technical change

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ABSTRACT

The contemporary world is confronted by a double challenge: environmental degradation and social inequality. This challenge is linked to the dynamics of the First Deep Transition (Schot, 2016): the creation and expansion of a wide range of socio-technical systems in a similar direction over the past 200–250 years. Extending the theoretical framework of Schot and Kanger (2018), this paper proposes that the First Deep Transition has been built up through successive Great Surges of Development (Perez, 2002), leading to the emergence of a macro-level selection environment called industrial modernity. This has resulted in the formation of a portfolio of directionality, characterized by dominant and durable directions and occasional discontinuous shifts in addition to a continuous variety of alternatives sustained in niches or single systems. This historically-informed view on the co-evolution of single socio-technical systems, complexes of systems and industrial modernity has distinctive implications for policy-making targeted at resolving the current challenges.

## 1. Introduction

The contemporary world is confronted by a double challenge: environmental degradation and social inequality. If left unchecked these threaten to lead to exceeding the limits of various planetary boundaries (IPCC, 2014; Steffen et al., 2015; Haberl et al., 2017) and to increases in social conflict (Cramer, 2003; Østby, 2008; Dixon, 2009; Hsiang et al., 2013). Historically, similar pressures have often facilitated major socio-ecological catastrophes and collapses (Tainter, 1988; Chase-Dunn and Hall, 1997; Diamond, 2005; Butzer, 2012; Scheidel, 2017). Hence the central problem facing the world today: how to avoid repeating this pathway while still being able to address pressing sustainability development goals such as greener and cleaner production, sustainable consumption patterns, increased social justice or fairer distribution of welfare (United Nations, 2015).

In much of the existing literature the root causes of current challenges have been traced back to individual characteristics, dispositions and behavioural patterns (e.g. Penn, 2003; Stern, 2014), the functioning of societal subsystems such as economy (e.g. Piketty, 2014; Moore, 2015) or the particular "Western" mode of thinking (e.g. LaFreniere, 2007; Lamba, 2010). Recently an alternative viewpoint has been proposed (Schot, 2016; Schot and Kanger, 2018): that the double challenge is fundamentally linked to the First Deep Transition. This notion refers to the creation and expansion of a wide range of socio-technical systems for the provision of transport, energy, food, housing, healthcare, communications, etc., in a similar direction over the past 200–250 years. Examples of similar directions, currently still dominant, are mechanization, mass production coupled with individual consumption, increasing energy- and resource-intensity (linear production), and a growing ecological footprint.

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From the second half of the 18th century, the First Deep Transition initially emerged as a response and a partial solution to pressing challenges of the pre-modern era, such as poverty and lack of energy resources (Lintsen et al., 2018). However, as it unfolded over the 19th and 20th centuries it gradually generated a new set of problems. From the 1960s-1970s onward, the impact of the double challenge started to be gradually felt, expressed in increasing concerns about the environmental effects of new technologies (Carson, 1962), feasibility of sustaining continuous growth (Meadows et al., 1972), suitability of Western capital-intensive technologies to developing countries (Schumacher, 1973; Kaplinsky, 2011), or increasing inequality within and between countries (Acemoglu and Robinson, 2012; Stiglitz, 2012; Piketty, 2014). These concerns prompted a search for radical alternatives to existing socio-technical systems in various niches. These began to emerge around the notion of appropriate technology, wind and solar energy, organic food, and micro-finance, for example. The underlying assumption of the Deep Transitions framework is that through gradual accumulation and coordination, niches may contribute to a fundamental overhaul of existing socio-technical systems, introduce a new set of sustainable and just directionalities (Swilling and Annecke, 2012), and thereby give rise to the Second Deep Transition. Whether this will eventually happen, however, is contingent on present and future decisions.

Explaining the long-term evolution of socio-technical systems as a genesis, consolidation and crisis of the First Deep Transition requires a new conceptual framework, synthesizing insights from various literatures. By drawing on the Multi-level Perspective on socio-technical transitions (Rip and Kemp, 1998; Geels, 2005; Grin et al., 2010) and the Techno-economic Paradigm framework (Perez, 1983; Freeman and Louçã, 2001), we filled in the first part of the puzzle (Schot and Kanger, 2018) by developing an evolutionary institutionalist model that connects transitions in single systems to the dynamics of five successive long waves, or Great Surges of Development (Perez, 2002). In particular we argued that the paradigmatic principles of each surge (such as mass production at the beginning of the 20th century) are often pioneered in isolated niches and single systems (e.g. mobility system), and that their diffusion to other systems (e.g. food, housing) takes decades, corresponding to the 40–60 year cycle of surges.

However, this conceptualization remained partial insofar as its analytical focus was primarily on major historical discontinuities in systems change, i.e. transitions and surges. It largely neglected another crucial feature of the First Deep Transition: the existence of major between-surge continuities that constitute the fundamental structure of industrial societies (e.g. their reliance on fossil fuels), contribute to long-term trends (e.g. increasing mechanization), lead to persistent problems (e.g. rebound effects), and thereby fundamentally shape the evolution of socio-technical systems in the very long term (100 years and more). Continuities such as these have been discussed in literature on industrialization and modernization (e.g. Mokyr, 1990; Giddens, 1991; Misa et al., 2003; Stearns, 2013). Hence the focal task of this paper: to connect this literature to the evolutionary dynamics of socio-technical systems, thereby arriving at a more comprehensive Deep Transitions framework capable of conceptualizing both major discontinuities and continuities of systems change over the past 200–250 years.

We begin in Section 2 with an outline of the foundations of the Deep Transitions framework to highlight its distinctive features compared to existing approaches. Section 3 synthesizes insights from the literature on industrialization and modernization, and introduces the concept of industrial modernity as a macro-level selection environment, emerging from, and gradually expanding through, the dynamics of socio-technical systems. Building on this conceptualization, Sections 4–7 theorize the long-term evolutionary dynamics of Deep Transitions. The final Section discusses the policy implications of the Deep Transitions framework and provides broader reflections on the role of history in shaping the governance of large-scale transitions.

In order to achieve our goal we have chosen the strategy of appreciative theorizing in which "a theory is a tool of inquiry, and in skilful applied research that tool is used flexibly, bent to fit the problem, and complemented by any other tools that happen to be available and that appear to be useful" (Nelson and Winter, 1982: 46). The end goal of this strategy is to arrive at a "disposable theory" (Castells, 2000b: 6). In other words, the following will not be an article about articles: we will not be conducting a comprehensive, comparative and critical review of a large volume of literature only to end up discarding most of it. Instead we will be drawing directly (and admittedly, quite eclectically) on the insights of a wide variety of sources that we deem useful for constructing our framework. What matters to us at this point is not whether the resulting theory is complete – it is not – but whether it is useful in provoking new ways of thinking and opening up new directions of research on sustainability transitions.

## 2. Deep Transitions framework: the story so far[1]

The Deep Transitions framework is a story about the unfolding of industrial modernization, told from the perspective of socio-technical systems change. In many ways it is similar to existing sociological accounts (e.g. Giddens, 1991; Beck, 1992) in that it foresees the possibility for a major rupture in the fabric of modern societies – the Second Deep Transition – but it stops short at proclaiming the emergence of a totally new societal formation such as a post-industrial (Bell, 1973) or network society (Castells, 2000-2004Castells, 2000aCastells, 2000-2004). Modernity transformed but not transcended is how the Deep Transitions framework is positioned in the modernity/post-modernity debate. That being said, the framework also combines specific features that distinguish it from existing analyses of long-term change.

First, the Deep Transitions approach is fundamentally socio-technical, focusing on the co-evolution of actors, technologies and institutions (Geels, 2004: 903). This stands in contrast to much of the existing macro-historical and macro-sociological literature that either, 1) focuses on "social systems" abstracted from their material context, e.g. Polanyi's Great Transformation narrative (2001/1944)Polanyi, 2001Polanyi's Great Transformation narrative (2001/1944) as an interaction between the market and the state); 2) subsumes socio-technical dynamics under a more general process, e.g. Giddens (1991) treating industrialism as one of the four basic

[1] The following section is expanded from Schot and Kanger (2018).

**Table 1**
Rules and socio-technical systems.

| Concept | General definition | Example |
|---|---|---|
| Rule | A humanly devised constraint that structures human action leading to a regular pattern of practice, present in a single socio-technical system | A drive to optimize fuel efficiency in the automobility system |
| Meta-rule | A single rule present in multiple socio-technical systems | Imperative to use fossil fuels (e.g. in agriculture, energy provision and mobility systems) |
| Regime | Relatively stable and aligned sets of rules directing the behaviour of actors along the trajectory of incremental innovation, present in a single socio-technical system | Mass production as defined in the US automobile industry at the beginning of the 20th century |
| Meta-regime | Rule-sets present in multiple socio-technical systems, coordinating their development and leading to a shared directionality | Global mass production in various systems (e.g. food, mobility, communications) after World War II, giving rise to throwaway consumer culture |
| Socio-technical system | Configuration of actors, technologies and institutions for fulfilling a certain societal function; manifestations (phenotype) of regimes | Systems of individual passenger transport with somewhat different national characteristics in post-war USA, the Netherlands and Germany |
| Complexes of systems | Configurations of socio-technical systems, manifestations (phenotype) of meta-regimes | The virtuous cycle of expansion of the automobile system and the housing system in USA, starting from the interwar era |

institutions of modernity, alongside capitalism, surveillance capacities and control of the means of violence); or 3) reduces technological aspects to a function of some social system, e.g. Wallerstein's (1989) analysis that sees the industrial revolution as an epiphenomenon of capitalist world-economy).

Second, a distinction between the genotype and phenotype of socio-technical systems provides an important dimension of depth to the framework. From the Deep Transitions perspective, a socio-technical system with certain characteristics in a certain locality at a certain point in time is seen as an expression (phenotype) of underlying rules and rule-sets (genotype). This argument echoes the distinction between 'system' and 'regime' in the original formulation of MLP (Rip and Kemp, 1998: 340; Geels, 2004) but goes beyond it by recognizing the differing degrees of scope and systemicity of rules. The Deep Transitions framework is based on the four-fold distinction between rules, meta-rules, regimes and meta-regimes, manifested either in single or interconnected systems. A Deep Transition can thus be viewed as a process whereby rules emerge, diffuse and become aligned, thereby providing single systems and interconnected complexes of systems with a specific long-lasting set of directions. Table 1 presents a summary of these concepts, including a formal definition and an empirical example of each.[2]

Third, the Deep Transitions framework aims to capture socio-technical dynamics on three scales: single systems, interconnected systems and industrial modernity. In so doing it draws together literatures that so far have remained fairly separate from each other, leading to novel insights about long-term systems change. We have previously combined the Multi-level Perspective (MLP) on socio-technical transitions (Rip and Kemp, 1998; Geels, 2005; Grin et al., 2010) with the Techno-economic Paradigm (TEP) framework (Freeman and Louçã, 2001; Perez, 2002) into an evolutionary multi-level model of surges (Schot and Kanger, 2018). This model describes how isolated niche practices align into rule-sets that, in surges lasting about 40–60 years, coordinate developments in a broad array of socio-technical systems (the approximate duration of one Great Surge of Development).

More specifically, we proposed that new rules emerge simultaneously in a wide range of niches and first transform single systems. For example, although the principles of interchangeability and moving work to workers were already known in the 18th and 19th centuries (Alder, 1997; Nye, 2013), it was only at the beginning of the 20th century that Henry Ford brought them (and various other rules) together into a regime of mass production. Interaction between regimes in multiple systems gradually leads to the emergence of rules and rule-sets shared between the systems, i.e. meta-rules and meta-regimes. For example, from the 1920s the principles of mass production were extended to the food system (e.g. tractors, new breeds of tomatoes and chicken amenable to a standardized production process) (Nye, 2013). Moreover, the revolution in land-based transport also allowed the extension of markets for agricultural products, creating new types of linkages between food and mobility systems (Mazoyer and Roudart, 2006). Finally, the dominant meta-regime begins to shape its broader macro-environment, called a "socio-technical landscape" (Rip and Kemp, 1998), through two mechanisms: sedimentation and feed-in. Sedimentation refers to the adding of another layer to the landscape, e.g. mass production and a car-based mobility system has created new patterns of urbanization that did not exist before. Feed-in refers to contributing to an already existing macro-trend generated by existing layers, e.g. the role of cars in the increase of greenhouse gas emissions (which had been rising from the beginning of the Industrial Revolution) (see Table 3 for more details).

Despite making the first steps towards conceptualizing the links between system dynamics and their broader environment, the explanatory focus of our model remained mostly restricted to a single surge. There are two reasons for this, both related to the underlying frameworks used for the synthesis. First, both MLP and TEP are focused on discontinuous changes – transitions in single systems and Great Surges of Development. As such neither the frameworks taken separately nor the synthesis were conceptually sensitized to address the possible existence of historical continuities, extending beyond a single transition or surge. Second, both frameworks have a relatively impoverished view of exogenous macro-level factors. Whereas the TEP approach largely ignores this

[2] Note, however, that the co-evolutionary approach of the framework also includes another direction of causality: ongoing technological experimentation with system elements or the build-up of new systems might lead to the introduction of new rules or the modification of existing ones.

aspect (but see Freeman and Louçã, 2001: 124–130, for an important exception), in MLP the notion of a socio-technical landscape is often reduced to a set of exogenous factors shaping the interaction of niches and regimes, but not being shaped by them in the short and medium term (e.g. the typology of landscape change introduced by Geels and Schot, 2007: 403–404). To date, however, both MLP and TEP have had relatively little to say on how single and interconnected systems shape the landscape itself. This is a key question for the Deep Transition framework. We suggest that in order to understand the long-term dynamics of Deep Transitions, we must first further endogenize the socio-technical landscape. This task is undertaken in the next section.

## 3. Industrial modernity and its main features

In mainstream sociological literature, society is commonly divided into the realms of economy, politics and culture. Depending on the analytical emphasis, the story of modernization can then be told as the economic narrative about the spread of capitalism, a political narrative of global democratization, or a cultural narrative on the emergence of post-traditional and increasingly secular societies. Implicit in all these narratives is the idea of the relative interdependence of societal subsystems: despite the fact that economy, politics and culture interact, each subsystem also operates according to its specific internal logic.[3] From the evolutionary perspective, economy, politics and culture can be viewed as macro-level selection environments, each selecting for particular units or traits (e.g. modes of production and specific business models in economy, modes of participation and specific voting procedures in politics, modes of representation and specific artistic works in culture).

In MLP, the distinction between societal subsystems was mobilized somewhat differently as the framework was originally developed to explain socio-technical system shifts. Here the notion of a socio-technical regime as an aligned rule-set was conceptualized as the partial intersection of regimes from different "societal" domains, i.e. technological, science, policy, user and market, and socio-cultural regimes (see Fig. 1). In other words, the partial alignment between different regimes was seen to constitute a new hybrid socio-technical regime, shaping the structure and driving the directionality of a socio-technical system. A similar idea was also implicit in the TEP literature that, however, focused on meta-regimes guiding multiple systems: for example, after World War II many socio-technical systems in Western industrialized countries (e.g. mobility, food, energy) were driven by the same combination of mass production, economies of scale, and a social contract between the state, entrepreneurs and labour in the context of relatively closed national markets (Perez, 2002).

In this section we would like to extend this logic one step further by focusing on the continuities in industrial societies that extend beyond specific systems and single surges. Our hypothesis is that throughout the 200–250 year process of industrialization, socio-technical systems have generated their own macro-level selection environment, one that is directly related to the evolution of single systems and complexes of systems. We call this selection environment the industrial modernity.

Industrial modernity is defined by a number of components covering multiple surges and having such a wide scope that they have come to characterize almost any socio-technical system in any industrial society. Its genotype consists of a number of fundamental assumptions and rules about industrial societies that manifest themselves as particular structural features, long-term trends and persistent problems. These rules can be thought of as the crystallized wisdom of industrial societies accumulated over centuries, a collection of its "best practices". However, this notion should be used with a heavy caveat, because, in this context, "best" does not mean "good" or "objectively true" but rather "very durable" and "fit for purpose". For example, Latour (1993) argues that it was the symbolic (but objectively speaking mistaken) separation between Nature and Society that allowed modernity to emerge as it enabled unprecedented societal experimentation without automatically assuming that this would upset the natural balance.

We propose that the notion of industrial modernity addresses a gap between different literatures. On one hand, in socio-technical systems literature exogenous factors are either virtually neglected (TEP) or undertheorized – in MLP the notion of landscape simply lumps together very different macro-structures and macro-trends. On the other hand, macro-historical and macro-sociological literature too often focuses on the "social" (i.e. economic, political, cultural) dimensions of modernity, overlooking or downplaying the importance of technologies, socio-technical systems and infrastructures (but with notable exceptions: see Brey, 2003, for a critical review of the role of technology in modernity theory). By invoking the notion of industrial modernity, we thus partially endogenize the notion of landscape. We suggest that industrial modernity constitutes a selection environment with particular characteristics and internal dynamics that is relatively independent from other societal realms: in other words, similarly to the "economic", "political" or "cultural" history of modernization there is also a "socio-technical" one. This assumption is empirically supported by work in the socio-metabolism literature where studies of various countries (e.g. Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2016; Haberl et al., 2017) have shown that, despite widely differing economic and political conditions (e.g. planned vs. market economy, totalitarian vs. democratic regime, initiators vs. latecomers), over time industrialized countries tend to converge towards fairly similar materials and energy usage profiles. We would interpret this as an indicator that these countries share participation in the same socio-technical macro-level selection environment of industrial modernity.

As the concept of industrial modernity has not been used systematically in prior literature, it is not possible to draw on a single authoritative source to outline its basic features. Instead we have reconstructed these characteristics on the basis of a diverse body of

[3] To give a few examples: Bell (1973) (see also Waters, 1996: 35) distinguishes between techno-economic, political and cultural realms of society and argues that internal developments in one can pose problems for others (e.g. the growing importance of science and technology in the techno-economic realm would pose increasing management problems for polity). Castells (2000b) divides society into relationships of production/consumption, power and experience, with technology cross-cutting all three. Michael Mann, 1986; Mann (1986, 1993, 2012, 2013)Mann, 1986Mann (1986, 1993, 2012, 2013) identifies four main sources of power: economic, ideological, military and political.

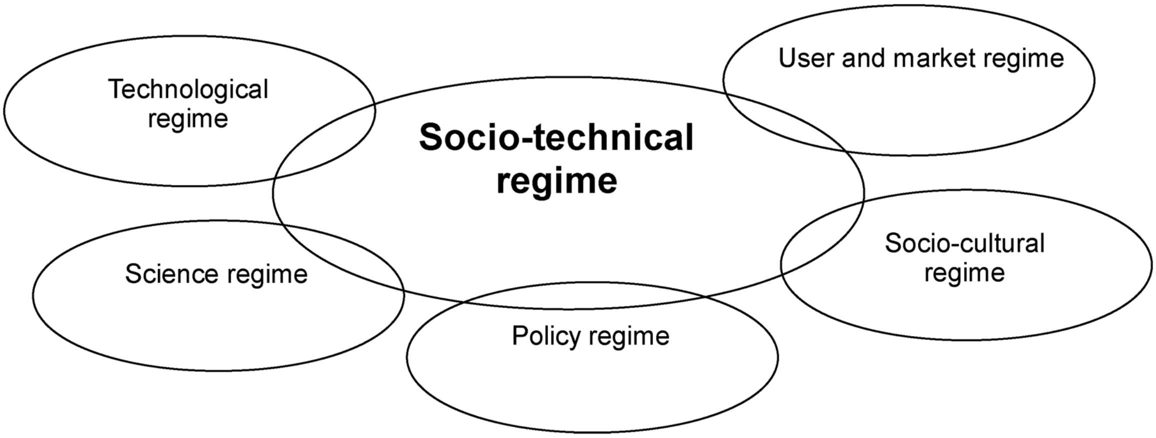


**Fig. 1.** Alignment of different rule regimes into a socio-technical regime (redrawn from Geels, 2004: 905).

literature on industrialization and modernization, including Science, Technology and Innovation Studies (Collingridge, 1980; Perrow, 1984; Latour, 1993; Unruh, 2000; Grübler, 2003; Arthur, 2009), history (of technology) (Adas, 1990; Mokyr, 1990, 2017; Misa et al., 2003; McNeill and McNeill, 2003; Nye, 2006; Stearns, 2013; McClellan and Dorn, 2015), sociology (Harvey, 1990; Giddens, 1991; Beck, 1992; Castells, 2000–2004Castells, 2000aCastells, 2000–2004; Sanderson, 2005), and various socio-ecological approaches (Fischer-Kowalski and Haberl, 2007; Lamba, 2010; Moore, 2015; Haberl et al., 2017). Although they differ considerably in terms of their empirical focuses and ontological assumptions, all of them reveal some broad and long-lasting features of industrial societies. We use the Deep Transitions perspective as discussed above to organize this variety of insights. Hence we treat industrial modernity as an intersection of five subsystems: 1) resources, science and technology; 2) economics, business and industry; 3) policy, regulation and governance; 4) user practices, consumption and everyday life; 5) culture. Furthermore, we distinguish between the genotype and phenotype of industrial modernity, i.e. between its foundational beliefs and driving rules and its empirically observable features (long-term trends and persistent problems, both of which are often created by the interaction of many rules). Table 2 provides an overview of the results of our preliminary literature survey.

Four disclaimers should be made. First, this list should only be considered a rough approximation, not a full account, which remains to be fleshed out in future work. Second, all these features should be considered ideal types: that is, the table focuses on the overall trends but downplays the internal variation (i.e. the belief in technological progress is likely to be spatially unevenly distributed and fluctuate over time). Third, we hasten to remind that industrial modernity should not be seen as an ahistorical structure with fixed characteristics: instead it is a dynamic and changing macro-selection environment that co-evolves with niches, regimes and meta-regimes.

Fourth, and most importantly, it should be kept in mind that the notion of industrial modernity only partially endogenizes the notion of a socio-technical landscape. That is, similarly to regimes and meta-regimes, it should be seen as a partial intersection of societal sub-systems, only including rules, trends and problems related to the application of science and technology.[4] In our account, the various socio-technical systems of industrial societies are the genesis of industrial modernity. In the Deep Transition framework, we analyse their impact much like Hughes did in his “American Genesis” (Hughes, 1989). He showed how the United States became imbued with a drive for order, system, control and technological enthusiasm, and how this was paralleled with the development of what he calls Large Technical Systems. The United States became a technological nation. Similarly, we would like to argue that the First Deep Transition created a technological world and culture in which certain underlying assumptions and rules, embedded in a wide range of socio-technical systems, became the modern industrial way of organizing the production, distribution and consumption of goods and services, satisfying societal needs.

We contend that the First Deep Transition has been pervasive and changed our entire landscape as we know it. But in so doing it has interacted, and continues to interact, with major trends in other macro-level selection environments; these include the increasing reach of capitalism, the development of international institutional frameworks, or the hybridization of global culture all of which are relatively independent from the operation of industrial modernity. For example, although the interaction of industrialization and capitalism has historically accelerated technological innovation, the Deep Transitions theory is not about theorizing the emergence and evolution of capitalism itself: this explanatory job has been performed by other frameworks such as world-systems or world-ecological approaches (Sanderson, 2005; Moore, 2015). In contrast to the sociological traditions of macro-level (e.g. Bell, 1973; Castells, 2000–2004Castells, 2000aCastells, 2000–2004) or grand theory (Parsons, 1951; Giddens, 1984; Luhmann, 1995), we do not aim to theorize society as a whole, grasping the totality of interactions between socio-technical, economic, political and cultural realms, but limit our research lens mainly to the parallel evolution of single socio-technical systems, interconnected systems and industrial modernity.

[4] Admittedly this leads to similar operationalization problems as encountered in MLP with its central concept of “regime” (see Holtz et al., 2008; Fuenfschilling and Truffer, 2014). As such the quantification of rules and meta-rules is one of the explicit methodological ambitions of the Deep Transitions project (see Schot and Kanger, 2018: 1057).

**Table 2**
The basic features of industrial modernity.

| Dimensions of industrial modernity | Beliefs and guiding rules | Long-term trends and directionalities | Pervasive and persistent problems |
|---|---|---|---|
| Resources, science and technology | 1. Belief that societal problems, however deep and complex, can be solved through the application of science and technology<br>2. Belief that any human task can and should be substituted with technologies, whenever possible, to increase productivity and efficiency<br>3. A drive to ensure that technology could operate independently of natural influences<br>4. Techno-neutrality: a view of science, technology and innovation as inherently value free means to any goal | 1. The emergence of a distinctive socio-metabolic profile in industrial societies, characterized by reliance on fossil fuels and non-organic inputs, increasing energy and resource-intensity, ecological footprint and waste production<br>2. Mechanization: increasing number, complexity, variety, scale, scope, interconnectedness, capital-, skill- and knowledge-intensity of individual technologies and socio-technical systems<br>3. Increasing use of formal science as a direct input to technological research and development activities in a wide variety of socio-technical systems<br>4. Emphasis on labour productivity as a prime metric of efficiency in production (vs. resource efficiency)<br>5. Normalization of temporary unemployment due to technological displacement, involving a constant pressure towards the upgrading of education and skills<br>6. Widening distance between production, distribution and consumption activities as they have increasingly come to be organized on a global level in global value chains<br>7. Preoccupation with economic growth as end and means on the state level as indicators of "societal progress" and "development"<br>8. Increasing investments in R&D by the State, the results of which are appropriated by the private sector under the rubric of innovation<br>9. A largely reactive approach to the consequences of science, technology and innovation: impacts are perceived as negative externalities to be solved by the State through regulation, and developers of new knowledge and technologies are generally not to be held responsible for societal impacts<br>10. Regulatory emphasis on the volume and speed (vs. directionality) of innovation<br>11. Increasing reliance on various technologies and infrastructures for the "normal" conduct of everyday life and for satisfying the "basic human needs" of society, however defined<br>12. Acquisition of ever more goods and services in individual consumption<br>13. Dominance of a throwaway consumer culture (vs. reuse and recycle)<br>14. Increasing sense of time-space compression and acceleration of social life | 1. Techno-fixes: repeated attempts to solve problems created by existing technologies and infrastructures through the introduction of newer and more complex technologies<br>2. Amara's law: constant overestimation of the promises and perils of new technologies in the short term (e.g. hype cycles, fears of technological unemployment), underestimation of long-term impacts<br>3. Rebound effects: various improvements in technological productivity and energy efficiency frequently tend to be offset by rises in demand stimulated by these improvements<br>4. Normal accidents: individual machines become safer whereas the risks for systemic failure keep increasing<br>5. Collingridge dilemma: the impact of a new technology cannot be easily predicted until it is widely adopted; however, at that stage changing it is very difficult<br>6. Spatial separation of the benefits of new technologies from their socio-environmental damages leads to a decrease in visibility, political accountability and responsibility<br>7. A lock-in to carbon-intensive socio-technical systems requiring a large yearly flow of energy and materials to keep them in operation, contributing to climate change and resource depletion<br>8. A lock-in to capital-intensive solutions that generate high accessibility thresholds because they assume a certain level of purchasing power; they also have built-in assumptions about the availability of expensive infrastructures |
| Economics, business and industry | 1. Belief in firms as drivers of innovation<br>2. Belief in limitless supply or substitutability of resources<br>3. Belief in the importance of promoting and participating in global value chains<br>4. Assumption that waste is not a fundamental problem | | |
| Policy, regulation and governance | 1. Assumption that "market failure" is a key regulatory problem for R&D and many infrastructures (e.g. education, transport, communications)<br>2. Belief in the inherent uncertainty of basic R&D and in the necessity not to influence the direction of the search process<br>3. Belief that experts should provide neutral advice and political decision-making should be based on the evidence provided by experts | | |
| User practices, consumption and everyday life | 1. Anticipation of an ever-increasing availability of goods and services for lower prices<br>2. Belief in consumerism as a form of democracy and consumption as a matter of individual choice | | |
| Culture: general foundational assumptions and symbolic meanings | 1. Separation of Nature and Society<br>2. Efficiency, order and control over one's environment as fundamental and positive values<br>3. Instrumental view of nature as a resource to be harnessed and manipulated by humans for humans<br>4. Belief in general societal progress through machines as the measure of men: the application of Reason would lead to emancipation, empowerment and self-realization | | |

## 4. Deep Transition as a very long term path dependency

We are now in a position to extend the Deep Transition framework with four propositions on the macro-dynamics of Deep Transitions. We begin with the proposition that industrial modernity is built up through successive Great Surges of Development. This results in the addition of new layers to the socio-technical landscape as well as the modification of existing ones. For example, the new Information and Communication Technology infrastructure, built during the 5th surge, remains dependent on the underlying energy grid, created during the 3rd surge. Therefore, the addition of a new communications layer simultaneously reinforces the already existing one of energy provision. However, the opportunities offered by ICT also enable the transformation of the energy

**Table 3**
Summary of the main propositions of the Deep Transition framework (based on Schot and Kanger, 2018, and this paper).

| No | Proposition | Empirical example |
|---|---|---|
| 1 | Before the Great Surges of Development (GSoD), rules emerge and compete in several niches of individual socio-technical systems without much coordination | The varied origins of the basic principles of mass production, e.g. interchangeability in the French military in the 18th century, moving work to workers in US meat industry in the 19th century |
| 2 | During irruption (1st phase of GSoD) the emerging and incumbent rules and regimes come to compete against each other in individual systems, resulting in transitions | The alignment of many formerly independent rules (e.g. electrification, work process optimization, sub-division of tasks) into the regime of mass production in Ford's Highland Park factory between 1913-1915 |
| 3 | During frenzy (2nd phase of GSoD), many rules increasingly start to cross the boundaries of a single system and partially align to each other, leading to the formation of alternative, possibly competing rule-sets | Attempts of varying success to apply mass production, as practiced in the automobile industry, in agriculture, food processing, consumer durables and housing in the 1920s as specialty production gradually starts to wane |
| 4 | Two mechanisms for achieving more coordination across the boundaries of a single system are structural and functional couplings | Beginning from the interwar era, the mechanization of transport enlarges the markets for agricultural products (functional coupling between mobility and food systems); both systems benefit from a shared infrastructure of paved roads (structural coupling) |
| 5 | Additional mechanisms, further facilitating and accelerating the creation of between-system links, are the aggregation and intermediation work of inter- and transnational organizations | League of Nations, International Labor Organization, Marshall Plan, Productivity Mission and Fulbright Program as channels of influence by which mass production diffused to Europe |
| 6 | Competition between meta-rules is finally resolved at the turning point of a GSoD, tipping the scales decisively in favour of one meta-regime that becomes dominant | WWII requirements increasing the need for standardized production of machines and goods (e.g. tanks, airplanes, food) in the Transatlantic region (e.g. USA, Germany, France, UK) |
| 7 | During synergy (3rd phase of GSoD) the dominant meta-regime selects niches compatible with its logic, diffuses to various systems and starts to shape the landscape | Post-war era: product standardization in agriculture (e.g. new breeds) to enable a better applicability of mass production techniques, take-up of some principles of mass production in the housing system, and emerging environmental impacts of mass production/consumption |
| 8 | During maturity (4th phase of GSoD) the dominant meta-regime loses its grip and the cycle re-starts with other niches, systems and rules becoming central to the new surge. The formerly dominant meta-regime shapes the new surge as part of the landscape through feed-in and sedimentation mechanisms | Oil shocks of 1973 and 1979 signal the crisis of traditional mass production; emphasis shifts to new information and telecommunications technologies as the new hotspot of innovative activities. However, many new ICTs and their components are mass produced |
| 9 | Industrial modernity as a macro-level selection environment is built up through successive Great Surges of Development, creating a very long term path dependency in the evolution of socio-technical systems | The success of mass production contributes to beliefs about continuous societal progress, technology-fuelled economic growth, and consumer expectations of the availability of increasing variety of goods at lower prices |
| 10 | Over the very long term, the First Deep Transition has created a dominant set of directionalities that gradually intensifies the double challenge | The ongoing contribution of mass production to environmental degradation through the creation of waste, pollution and resource depletion, and the development of capital-intensive products and services for the wealthy |
| 11 | The aggregate outcome of the evolution of Deep Transitions is the formation of a portfolio of directionality | Mass production has become a fundamental part of industrial societies yet it has been, and continues to be, challenged by both internal and external alternatives (e.g. automated factories, specialty production, appropriate technology movement) |
| 12 | The double challenge stimulates the emergence of the Second Deep Transition | The current problems of mass production might contribute to reshaping the broader context in a manner that would eventually come to support the emergence of sustainable mass production (e.g. design for durability, circular economy, sharing economy, lowering of accessibility thresholds) in a range of socio-technical systems |

infrastructure to a certain extent, e.g. through the creation of a smart grid. This means that over the period of 200–250 years, the features of industrial modernity have not only gradually become strengthened and deepened but also broadened in particular ways.

The idea of the long-term, gradual and cumulative evolution of industrial modernity implies that only some of its features were already installed during the 1st surge whereas many have been added later. For example, an absolute increase in resource and materials usage has indeed been a characteristic feature of industrialization from its very beginning in the second half of the 18th century (Haberl et al., 2017). On the other hand, there was not much direct and systematic interaction between science and technology during the first two surges: it was only in 1874 that the Friedrich Bayer Company established the first industrial research laboratory (McClellan and Dorn, 2015: 344–348). From the 3rd surge, however, the application of theoretical knowledge to practical ends became increasingly characteristic of industrial modernity, with a somewhat paradoxical result of later observers starting to hail it as one of the defining features of "post-industrial", "information", "knowledge" or "network" societies (Bell, 1973; Castells, 2000–2004Castells, 2000aCastells, 2000–2004; see also Webster, 2015: 34–36, 60–65, 134–135, for an historically-informed critical elaboration of this point).

We suggest that the overall directionality of the First Deep Transition was loosely established with the 1s surge. Subsequently, each time a mature surge started to exhaust itself and competing alternatives (re)appeared, the choice was increasingly biased towards certain features of industrial modernity. As each new surge added weight to the existing trajectory, it also made the outcomes of this large transformation less and less reversible, thus creating a very long term path dependency (or set of shared directions) as reflected in the durable socio-technical patterns of industrial societies. In effect, through successive surges industrial modernity became an increasingly powerful selection environment. Fig. 2 visualizes this proposition.

The idea of the existence of a very long term path-dependency, related to the consolidation of industrial modernity, has particular

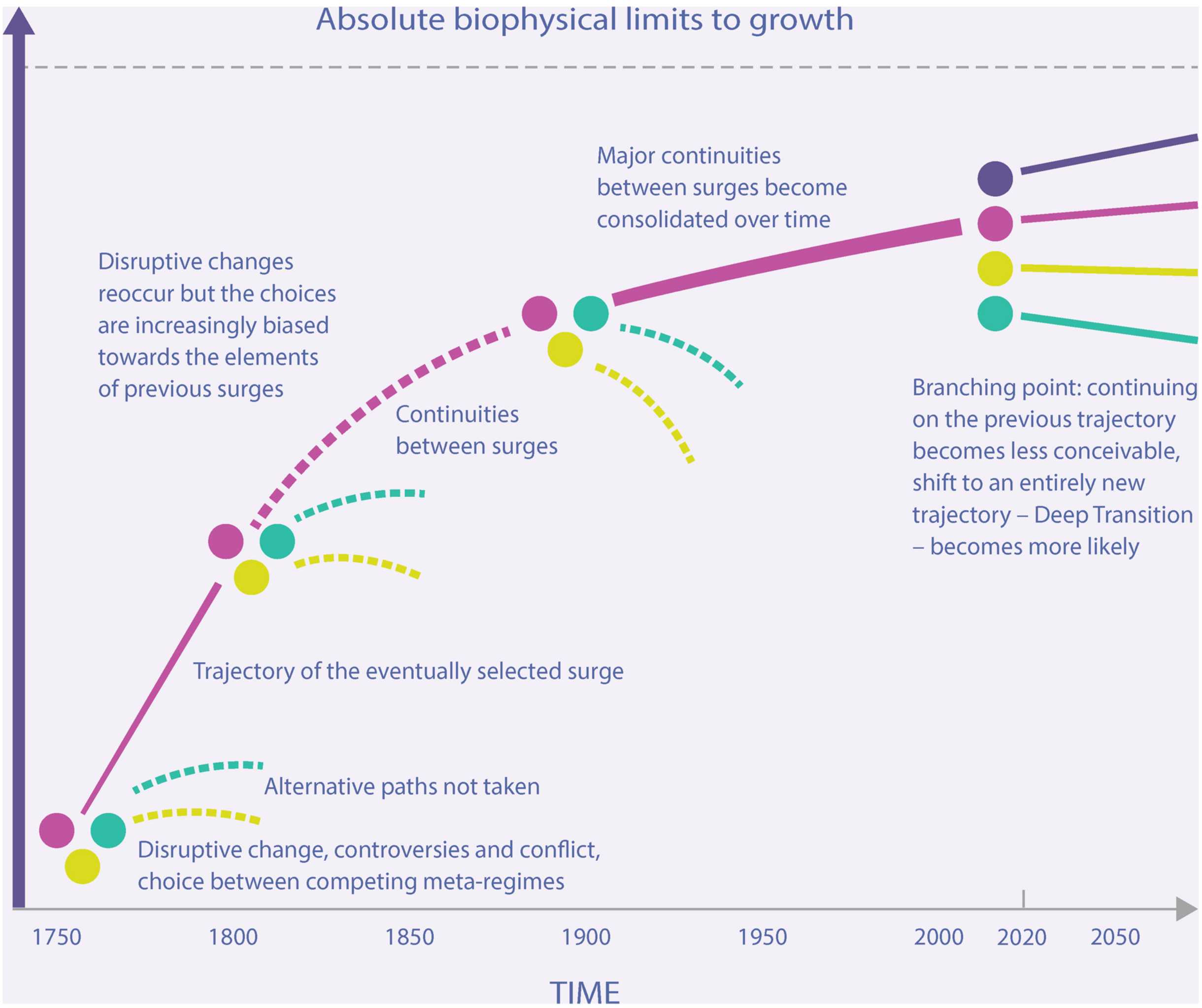


**Fig. 2.** Cumulative effect of Great Surges of Development: A very long term path dependency.

implications on our understanding of socio-technical systems change. It suggests that when existing meta-regimes mature, enter a crisis and are challenged by alternative solutions, the resulting controversies are likely to be resolved in a manner that would sustain the basic characteristics of these meta-regimes. The historical evolution of mass production provides a good example. Having enjoyed its heyday during the long boom after World War II, the oil shocks of 1973 and 1979 signalled a crisis of traditional mass production, based on special-purpose machines, semi-skilled workers, standardized goods and mass markets. A number of alternative strategies, ranging from conservative to radical, were employed to address this problem: the former included the offshoring of manufacturing activities to minimize labour costs or supplanting mass production with some principles borrowed from the craft tradition (e.g. Volvo stopping the assembly line and experimenting with team assembly) (Nye, 2013). At the other end of the spectrum was the vision of a computer-enhanced fully-automated factory, something that had been envisaged since the 1950s although constantly failing to realize (*ibid.*), and the envisioned future dominance of “post-Fordism”, based on craft production, skilled workers, customized goods and niche markets (Piore and Sabel, 1984; Hirst and Zeitlin, 1991). This process was interpreted as the re-emergence of an historical alternative to mass production, dating back to at least the 19th century (Sabel and Zeitlin, 1985).

Located between these two poles of incremental innovation and total transformation was “lean production”, a configuration of production principles (such as just-in-time supply, close buyer-supplier relationships, continuous improvement) pioneered in Toyota (Holweg, 2007; Nye, 2013). Its gradual adoption by many Japanese, European and American enterprises between the 1970s-1990s raised the productivity of labour and the quality of products while alleviating some major problems of the traditional version of mass production (e.g. the buffering of stocks, relative inflexibility). In terms of labour process, however, the basic characteristics of traditional mass production such as the work study, assembly lines, mass marketing, etc., were retained. Therefore, the adoption of the Japanese model has been argued to represent “an evolution within Fordism rather than a transformation of it” (Wood, 1993: 535). This argument can be extended to contemporary developments: for example, it is not difficult to see the currently fashionable Industry 4.0 concept and the envisioned rise of “cyber-physical systems” (Federal Government of Germany, 2014), or the expectations of the rise of "mass customization" (Fogliatto et al., 2012) as mass production with enhanced capacity for flexibility, individualization and customization. While improving the efficiency of production processes, this development on its own is likely to achieve very little in altering the dominant directionality of mass production, initiated during the 4th surge, towards increased resource consumption and resultant environmental impacts. Hence the recent developments can easily strengthen rather than reverse the long-term path-dependency first established a century ago with the emergence of a mass production/consumption society.

## 5. Deep Transitions and the double challenge

The First Deep Transition emerged as a response to the pressing issues of the pre-modern era. In many ways it was highly successful leading – over the long term, on average and in some areas – to massive increases in wealth and welfare, including a decrease in absolute poverty, high GDP, an increase in life expectancy, a decrease in infant mortality, access to high-quality food, clean water, cheap energy, mobility and communication services, sustained technological dynamism, social safety net, etc., etc. However, despite the sustained enthusiastic expectations of the contemporaries, the environmental and social problems were never eradicated but rather postponed or transferred as solutions to specific problems in certain locations, and at certain times tended to re-create the problems elsewhere and later on (e.g. the externalization of environmental costs to developing countries eventually affecting the developed countries through the degradation of global ecosystems). Therefore, we propose that, over the long term, the First Deep Transition – defined as the co-evolution of single systems, interconnected systems and industrial modernity – has created a shared set of similar directionalities that has tended to intensify, with stops and starts, the double challenge. That is to say, throughout the First Deep Transition, various socio-technical systems have partially contributed to environmental degradation and to the creation, transfer or amplification of social inequalities.[5] Note that the focal inequalities are not based on income or wealth distribution but related to differential access to socio-technical systems, differential gains from the system, and an uneven distribution of risks.

The combination of two propositions – the notion of a very long term path dependency and the contribution of socio-technical systems to the double challenge – would enable to explain why, historically, many niches have begun from promising to solve certain problems only to end up reinforcing them. For example, the car was initially perceived as a response to environmental issues in cities (Flink, 1990) and as a means of overcoming the rural isolation of farmers (Ling, 1992). But as the car-based mobility systems came to dominate in the USA, Europe and its various colonies, they started to contribute substantially to pollution and climate change instead. At present, road transport contributes to about 20% of the EU's total $CO_2$ emissions, being the only major sector where greenhouse gas emissions are still rising (European Commission, 2017). Moreover, these systems are characterized by new types of socio-spatial inequality (Ohnmacht et al., 2009; Geels et al., 2012; Sheller, 2015), e.g. the privatization of expenses related to car maintenance and services having a substantial impact on low-income households, or the non-proportional distribution of health-related risks for non-users of the car in the USA (Lutz, 2014).

Similarly, Information and Communication Technologies continue to be praised for their efficiency-enhancing capacities and deliberative potential. However, recent studies show that these technologies are associated with increased energy (Aebischer and Hilty, 2014; van Heddeghem et al., 2014) and materials consumption with no evidence for dematerialization (Magee and Devezas, 2017). ICTs have also been shown to intensify existing social inequalities, e.g. between 2010–2015 the ICT Development Index increased by 0.92 points for developed and 0.89 points for developing countries, but only 0.56 points for the Least Developed Countries (ITU, 2015: 56). Moreover, there is evidence that the returns from ICT usage are higher for privileged social groups than for lower social status users, even in countries where access to these technologies is virtually universal (Wei and Hindman, 2011; van Deursen and van Dijk, 2014; van Deursen and Helsper, 2015). In terms of our framework we would interpret these developments as indications that, over time, the potential alternative directions of development offered by new niches have been captured by the dominant evolutionary logic of the First Deep Transition after which their further development becomes aligned to it.[6]

## 6. Deep Transition as a portfolio of directionality

The previous two sections have addressed major continuities related to the evolution and structuring impact of industrial modernity. However, we should keep in mind that Deep Transitions are not only about continuities but also about discontinuities, involving transitions in single systems and great surges of development. Therefore, a Deep Transition should be more accurately seen as a co-evolution of niches, regimes, meta-regimes and industrial modernity that includes both dominant directions of development

[5] Echoing the disclaimer made at the end of Section 3, we again want to emphasize the claim about the limited role of socio-technical systems in contributing to the double challenge: while our framework addresses the relationship between socio-technical systems and the double challenge, we do not suggest that the former are the only cause of the latter. The Deep Transitions framework is not a theory of everything: through the introduction of the notion of industrial modernity, it partially endogenizes the socio-technical landscape, however, it also considers many macro-trends exogenous, that is, relatively independent from the dynamics of socio-technical systems and explained better by reference to other theories. A good example comes from Piketty (2014) who argues that unfettered capitalism naturally gravitates towards increasing inequality. Here inequality is explained mainly through the impact of (capitalist) economy as a macro-level selection environment.

[6] This interpretation goes beyond re-stating the well-known findings from the literature that technologies have unintended consequences (Kranzberg, 1986; Tenner, 1997; Sveiby et al., 2012) or that the radical potential of technologies tends to be "suppressed" by the social context (Winston, 1998). What our framework adds to these observations is that, in the context of the First Deep Transition, these consequences are likely to play out in a particular direction.

as well as a multiplicity of alternatives.

We therefore propose that the aggregate outcome of the evolution of Deep Transitions is the formation of a portfolio of directionality, defined as the collection of all possible directions of development offered by existing niches, regimes, meta-regimes and industrial modernity at a given moment of time. Over the course of a Deep Transition the portfolio undergoes change in terms of both content and size:

1 Major continuities refer to the long-term reproduction of some core meta-rules driving system evolution and innovation towards particular directions. That is, to some extent the portfolio is characterized by between-surge directionality, a dominant trajectory of Deep Transitions, as discussed above (see Table 2).
2 Great Surges of Development, in turn, can be thought of as temporary (40–60 years) alignments in the directionality of multiple socio-technical systems. Although the surges are somewhat discontinuous in relation to each other on the broader scale, they can be seen as variations on the theme of industrial modernity as some of the directionality of each surge is shared.
3 Niches and single systems can be seen as ever-present sources of variety for alternative solutions and trajectories of development: over time a niche can turn into a regime, a regime into meta-regime; conversely, a once dominant meta-regime can revert to a regime or even a niche. Niches can remain dormant for a long time, representing alternative paths not taken but also ones that may yet be taken in the future. Experimentation in niches also feeds the endless introduction of novelty: qualitatively new technological, organizational and institutional innovations, potentially opening up new directions of development. Throughout the course of a Deep Transition, the size of the portfolio of directionality therefore keeps increasing.

Fig. 3 visualizes this proposition.

The simultaneous attention to continuities, discontinuities and alternatives provides a more comprehensive view of socio-technical systems change, allowing for a richer and more nuanced analysis. In the case of mass production, attention to niches reminds us that mass production never dominated all systems, even in the USA as the paradigmatic country of the fourth surge (Jessop, 1992). The alternatives to (traditional) mass production (Scranton, 1997; Sabel and Zeitlin, 1997; Tolliday, 1998) thrived in particular locations and industries, enabling them to be scaled up when needed (e.g. lean production in the 1970s). The focus on major discontinuities reminds us that (for a particular time and for particular countries) the linkage between the certain technological, economic, political, user-related and cultural rules seems to be "natural", although with the next surge these connections can be unmade. For example, during the 4th surge, mass production seemed to be almost inevitably linked to high wages since the enterprises were mainly operating within specific national boundaries where the producers and consumers of products largely overlapped. However, from the 1970s the neoliberal economic policies allowed Western manufacturers to globalize their activities. This meant that the producers of a certain product were no longer necessarily its consumers, and therefore the link between mass production and high wages was broken (Nye, 2013). Finally, attention to continuities enables us to understand the cumulative socio-technical evolution. For example, in many ways the current surge, focused on ICTs, is still underpinned by the familiar practices of mass production (think of the production of microprocessors, hard drives, computers or mobile phones). The history of mass production is therefore also a history about the evolution of a portfolio of directionality.

## 7. The Second Deep Transition?

However, despite the existence of variety and the occurrence of periods of discontinuous change, we have suggested that the overall directionality of Deep Transitions has contributed to the double challenge. The history of past 200–250 years seems to indicate that the problems of the First Deep Transition cannot be definitively fixed within the framework conditions created by this very transition. This leads us to the final, and perhaps most speculative proposition: that the double challenge stimulates attempts to deal with the problems of the First Deep Transition, with the Second Deep Transition being one of the possible outcomes.

If this major transformation is indeed already underway, we should not only be expecting to detect new niches, regimes or meta-regimes, but also a rupture in industrial modernity. Whether this is already happening is an empirical matter in need of further investigation. However, during the past 50 years some significant signs of a deeper change can be detected. Examples of these include various alternative food, mobility and energy practices fundamentally challenging the operating principles of socio-technical systems of industrial modernity, the emergence of environmental social movements and their institutionalization in mainstream politics, or the globalization of the climate change agenda, including the recent Paris climate agreement on limiting global warming. The adoption of the UN Sustainable Development goals, which aim for a new type of development model that would leave no one behind, is another hopeful sign. Should these separate developments manage to gain dominance and become interlinked, the Second Deep Transition may get a new push, and this would create a fundamentally different macro-level selection environment for the future evolution of socio-technical systems: a different type of industrial modernity.

At this point our non-teleological and non-determinist credentials are worth stressing: the future is yet to be forged. Yet this does not equate to saying that each and every future avenue is equally likely to occur, since the possibilities for actors to exert their agency are considerably constrained by the socio-material outcomes of the First Deep Transition. While it is quite clear that the "business as usual" strategy of optimizing the existing socio-technical systems and externalizing the social and ecological costs cannot lead to a sustainable future, there is, in principle, nothing to stop the Second Deep Transition from failing, biophysical limits to growth from being reached, and large-scale societal collapse from occurring. The Second Deep Transition remains one possible outcome amongst many; moreover, it can be realized through multiple pathways. To illustrate these possibilities we will sketch two possible scenarios called Breakthrough and Transformation.

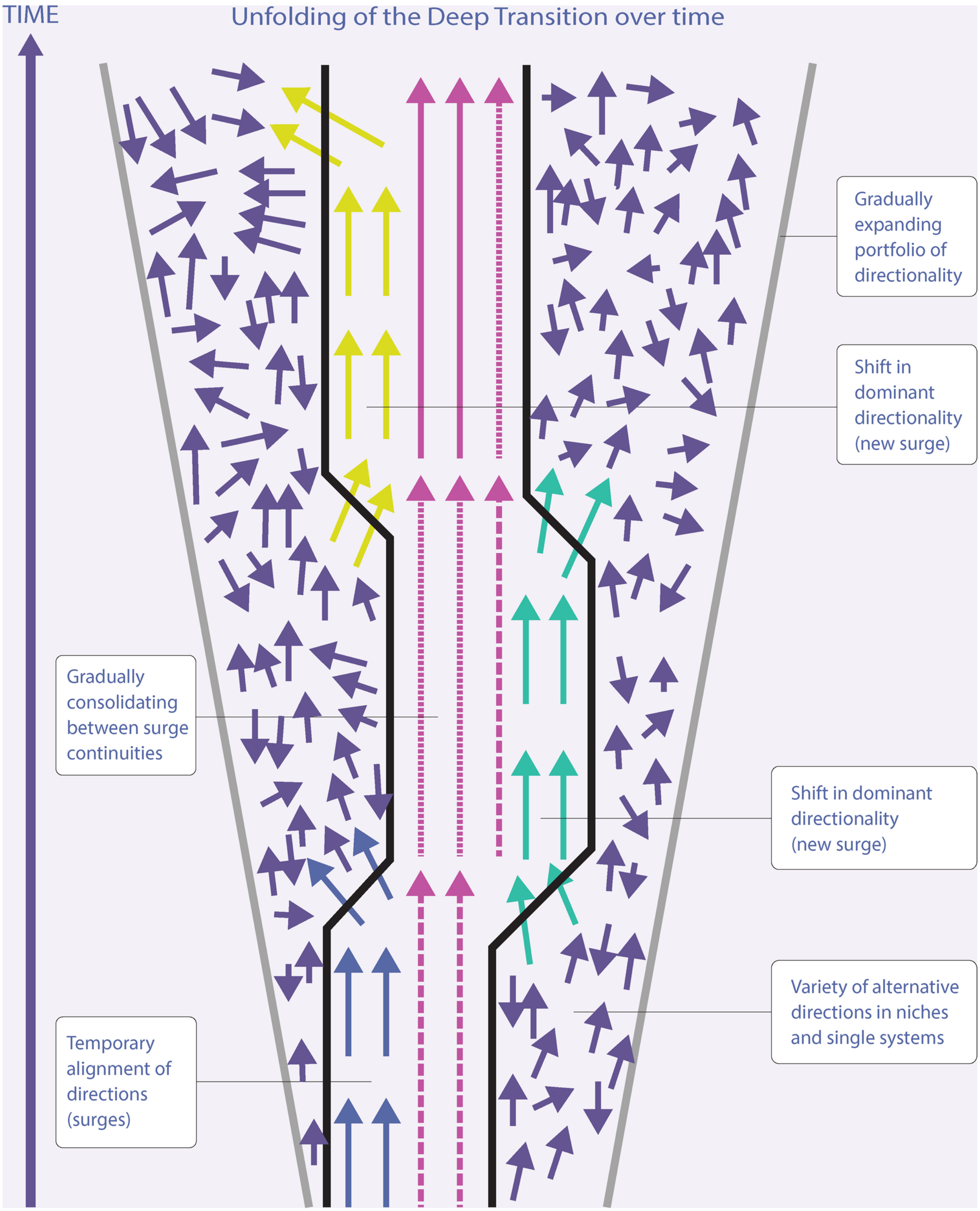


**Fig. 3.** Evolution of a portfolio of directionality.

The Breakthrough scenario implies a continuous expansion of the portfolio of directionality aimed at high-income consumers through mass production methods; these are capital- and skill-intensive, aim to reap economies of scale through large-volume production and rely on sophisticated knowledge systems and infrastructure. Actors respond to ecological challenges by introducing radical greener production and consumption patterns through the implementation of capital-intensive solutions (e.g. centralized energy production with big wind and solar farms, the expanded use of nuclear energy, various forms of geo-engineering and further development of the global value chain for waste products), and technologies that aim to mitigate *ex-post* the impacts of carbon-intensive development (e.g. carbon capture and storage). In this future, actors focus on the economic growth agenda, whereas distributional consequences of social and ecological costs, while recognized as important, ultimately remain of secondary importance.

The Breakthrough path contains the danger that it will undermine the social, political and ecological conditions on which it is built, strongly raising the likelihood of economic stagnation for a large part of the population, increased social inequality, resource-related conflicts, recurrent natural disasters and forced migration. Hence in this scenario, powerful political forces would need to be put in place to prevent and mitigate disasters, conflicts and wars, compensate for social excesses, and underwrite the legitimacy of the system. Given the high ecological and social costs to absorb, this pathway would imply the construction of a new relationship between the state, the market, and civil society, and most likely new forms of pro-active and entrepreneurial state action at the national and as well as city level, strong relationships between the state and business, and new technocratic supranational structures ensuring global coordination, which have proved difficult to achieve in response to recent social and economic challenges.

The Transformation pathway would address the double challenge of looming ecological crisis and deepening social inequality in a different way. In this scenario there will probably be less reliance on the state (at various levels) to redistribute *ex-post* the benefits of economic growth and manage the costs: instead distribution issues are dealt with *ex-ante*. Actors take more collective responsibility early on for the ecological and social impacts they generate. More emphasis might be put on social innovation. It might also imply a radical restructuring of current production and consumption patterns, and a move away from the principles of mechanization, labour-saving, reliance on fossil fuels, mass production and mass consumption, and centralized energy production towards more small-scale technologies and production, forms of collective and shared consumption, and decentralized energy production. If indeed "the greatest invention of the nineteenth century was the invention of the method of invention" (Whitehead, 1925: 98), then the realization of the Transformation scenario would require yet another re-invention of the way we innovate.

The dynamics outlined in Schot and Kanger (2018) and in this paper can now be drawn together into an overarching Deep Transitions framework, proposing the following causal sequence: interactions between various regimes link up to Great Surges of Development characterized by a dominant meta-regime. Successive meta-regimes come to constitute different layers of the socio-technical landscape whereby the broad selection environment of industrial modernity is formed. The co-evolution of niches, regimes, meta-regimes and industrial modernity, exhibiting a particular directionality, is called the First Deep Transition. Over time, the unfolding of the First Deep Transition generates the double challenge. As this challenge cannot be met within the conditions created by the First Deep Transition, the double challenge stimulates opportunities for the emergence of the Second Deep Transition that, should it succeed in becoming dominant, would fundamentally shape further multi-regime interaction. Fig. 4 provides a visual summary of the framework, whereas Table 3 presents all its propositions in more detail, together with empirical examples.

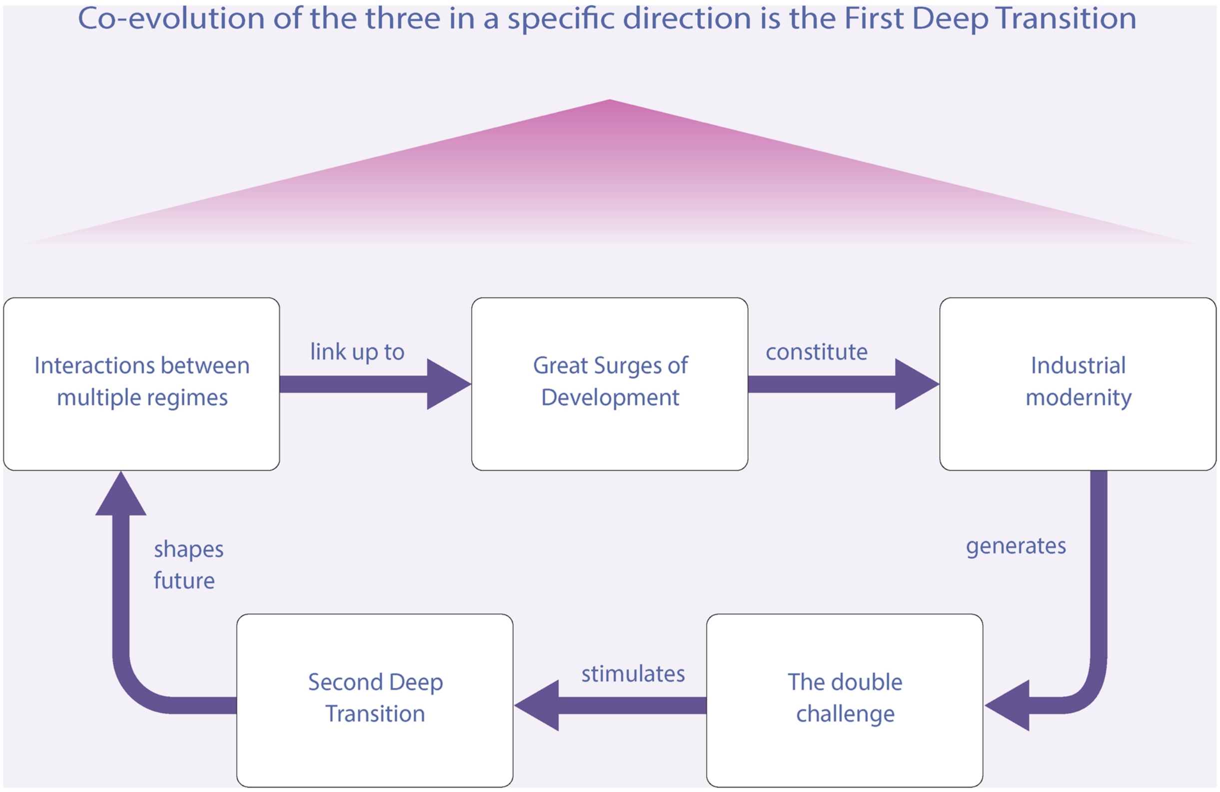


**Fig. 4.** Deep Transitions framework.

## 8. Deep Transitions: The role of history in policy-making

Our framework represents an attempt to capture the long-term evolution of socio-technical systems in a single framework, bringing together literatures on single systems, complexes of systems and industrial modernity. We are well aware of the dangers associated with this approach: some readers may feel that we have offered a structural explanation here that leaves far too little room for agency. They should be reminded that it is clearly human agents who develop niches, defend regimes and thus shape Deep Transitions. We agree with van der Vleuten (2018), that it is valuable and necessary to bring out the work of specific actors who are crucial for generating multi-regime and niche couplings, as well as de-couplings and shared and divergent directionalities. Yet we also believe in the need to bring out general historical patterns and structures. Our ontological approach can perhaps be characterized as evolutionary institutionalist, in which agency and structure constantly re-shape each other. Long-term change is not at the mercy of voluntaristic agency, nor is it wholly dependent on specific windows of opportunity; it is built up over time and through space through the ongoing interaction structure-agency interaction (Fürstenberg, 2016). Our analysis is intended to increase understanding about the constraints of, and opportunities for, long-term change processes. Since both agency and structure matter, neither detached fatalism nor boundless optimism will help much for thinking about policy options. We need cautious optimism and informed agency, which would allow and encourage engagement with ongoing transitions of individual and multiple systems.

The principles of historical imagination (Schot, 2016) are crucial for this engagement. The first principle is using history to provide an informed diagnosis of contemporary concerns. This is the concern about the long-term sustainability of our world. The Deep Transitions framework locates the unsustainability in the directionality of a complex of socio-technical systems, and hence focuses on the development of this complex. The second principle is that we need to see history as a set of scenarios with path-dependencies and hidden alternatives, which can be seen as roads not taken in the past, yet they may still become a seedbed for alternative developments in the future. Both path-dependencies and hidden alternatives are part of what we have called the portfolio of directionality. The third principle is that history shows us that radical change is possible, although it needs a specific set of conditions and triggers. It helps to overcome a sense of helplessness, a feeling that our past has put us in an iron cage or a prison, from which it is difficult to escape. The Deep Transition framework helps us to explore the “prison” and to identify opportunities for human agents for creating and nurturing new alternatives.

So what is the specific contribution of the Deep Transition thinking to policy engagements? On one hand, the double challenge is currently operating on an unprecedented scale and intensity. On the other hand, the portfolio of directionality is broader than ever, meaning that industrialized societies have also unprecedented capabilities for addressing global problems. The crucial issue is how to avoid the historically familiar outcome where initial solutions to particular problems only tend to create problems elsewhere or later on, thereby aggravating rather than alleviating the double challenge. Our analysis suggests that the expansion or optimization of existing socio-technical systems will not be even remotely enough. It also implies that neither the stimulation of radical niches to promote transitions in single systems, nor even the emergence of the next surge, will be sufficient. What is needed is to challenge the fundamental features of industrial modernity: we need a new theme, not another variation on the existing one. Only when the broad selection environment of industrial modernity itself is transformed can it stimulate the interaction between niches, regimes and meta-regimes in a manner that would alter the eventual directionality of the evolution of a broad range of socio-technical systems, constituting the backbone of industrial societies.

Environmental degradation and social inequality present a challenge to both the global North and South. However, it would be misleading to assume a division of labour where the South supplies all the problems and the North all the solutions. Not only has the North been historically implicated in creating problems in the South (Moore, 2015), historical evidence also shows that the role of peripheral areas in contributing to innovation, already during the First Deep Transition and in the context of a considerably lower degree of globalization, has traditionally been under-estimated (Arnold, 2005). The Second Deep Transition should therefore be seen as a global transnational response to the double challenge emerging from and being adapted in various locales. Indeed, the leading role of several Asian countries in the renewables field (Mathews, 2014), the idea of “just transitions” in the context of developing countries (Swilling and Annecke, 2012; Swilling et al., 2016), and the emergence of a transformative innovation policy framework (Schot and Steinmueller, 2018) can be seen as manifestations of this trend.

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## References


Acemoglu, D., Robinson, J.A., 2012. Why Nations Fail: The Origins of Power, Prosperity and Poverty. Profile Books, London.

Adas, M., 1990. Machines As the Measure of Men: Science, Technology, and Ideologies of Western Dominance. Cornell University Press, Ithaca, NY.

Aebischer, B., Hilty, L.M., 2014. The energy demand of ICT: a historical perspective and current methodological challenges. In: In: Hilty, L.M., Aebishcer, B. (Eds.), ICT Innovations for Sustainability: Advances in Intelligent Systems and Computing, vol. 310. Springer, pp. 71–103.

Alder, K., 1997. Innovation and Amnesia: engineering rationality and the fate of interchangeable parts manufacturing in France. Technol. Cult. 38 (2), 273–311.

Arnold, D., 2005. Europe, technology and colonialism. Hist. Technol. 21 (1), 85–106.

Arthur, W.B., 2009. The Nature of Technology: What It Is and How It Evolves. Free Press, New York.

Beck, U., 1992. Risk Society: Towards a New Modernity. Sage, London.

Bell, D., 1973. The Coming of Post-Industrial Society: A Venture in Social Forecasting. Basic Books, New York.

Brey, P., 2003. Theorizing modernity and technology. In: Misa, T.J., Brey, P., Feenberg, A. (Eds.), Modernity and Technology. The MIT Press, Cambridge, MA, pp. 33–72.

Butzer, K.W., 2012. Collapse, environment, and society. PNAS 109 (10), 3632–3639.

Carson, R., 1962. Silent Spring. Houghton Mifflin, Boston.

Castells, M. 2000-2004. The Information Age: Economy, Society and Culture, 3 volumes Second edition. Oxford, UK, and Malden, MA: Oxford University Press.

Castells, M., 2000b. Materials for an exploratory theory of the network society. Br. J. Sociol. 51 (1), 5–24.

Chase-Dunn, C., Hall, T.D., 1997. Rise and Demise: Comparing World-systems. Westview Press, Boulder, CO.

Collingridge, D., 1980. London. The Social Control of Technology. Frances Pinter Ltd.

Cramer, C., 2003. Does inequality cause conflict? J. Int. Dev. 15 (4), 397–412.

Diamond, J., 2005. Collapse: How Societies Choose to Fail or Survive. Penguin Books, London.

Dixon, J., 2009. What causes civil wars? Integrating quantitative research findings. Int. Stud. Rev. 11 (4), 707–735.

European Commission, 2017. Road Transport: Reducing CO2 Emissions From Vehicles. Available online:. https://ec.europa.eu/clima/policies/transport/vehicles_en.

Federal Government of Germany, The, 2014. The New High-Tech Strategy Innovations for Germany. Available online: https://www.bmbf.de/pub/HTS_Broschuere_eng.pdf.

Fischer-Kowalski, M., Haberl, H. (Eds.), 2007. Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar, Cheltenham, UK.

Flink, J.J., 1990. The Automobile Age. The MIT Press, Cambridge, MA.

Fogliatto, F.S., da Silveira, G.J.C., Borenstein, D., 2012. The mass customization decade: an updated review of literature. Int. J. Prod. Econ. 138 (1), 14–25.

Freeman, C., Louçã, F., 2001. As Time Goes By: From the Industrial Revolutions to the Information Revolution. Oxford University Press, Oxford.

Fuenfschilling, L., Truffer, B., 2014. The structuration of socio-technical regimes – conceptual foundations from institutional theory. Res. Policy 43 (4), 772–791.

Fürstenberg, K., 2016. Evolutionary institutionalism: new perspectives. Politics Life Sci. 35 (1), 48–60.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems. Insights about dynamics and change from sociology and institutional theory. Res. Policy 33 (6-7), 897–920.

Geels, F.W., 2005. Technological Transitions and System Innovations: A Co-Evolutionary and Socio-Technical Analysis. Edward Elgar, Cheltenham.

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Res. Policy 36 (3), 399–417.

Geels, F.W., Kemp, R., Dudley, G., Lyons, G. (Eds.), 2012. Automobility in Transition? A Socio-Technical Analysis of Sustainable Transport. Routledge, New York.

Giddens, A., 1984. The Constitution of Society: Outline of the Theory of Structuration. University of California Press, Berkeley and Los Angeles.

Giddens, A., 1991. The Consequences of Modernity. Stanford University Press, Stanford.

Grin, J., Rotmans, J., Schot, J., 2010. Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change. Routledge, New York.

Grübler, A., 2003. Technology and Global Change. Cambridge University Press, Cambridge, MA.

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V. (Eds.), 2017. Social Ecology: Society-Nature Relations Across Time and Space. Springer.

Harvey, D., 1990. The Condition of Postmodernity: an Enquiry Into the Origins of Cultural Change. Blackwell, Cambridge.

Hirst, P., Zeitlin, J., 1991. Flexible specialization versus post-Fordism: theory, evidence and policy implications. Econ. Soc. 20 (1), 1–56.

Holtz, G., Brugnach, M., Pahl-Wostl, C., 2008. Specifying “regime” – a framework for defining and describing regimes in transition research. Technol. Forecast. Soc. Change 75 (5), 623–643.

Holweg, M., 2007. The genealogy of lean production. J. Oper. Manag. 25 (2), 420–437.

Hsiang, S.M., Burke, M., Miguel, E., 2013. Quantifying the influence of climate on human conflict. Science 341 (6151) 1235367.

Hughes, T.P., 1989. American Genesis. A Century of Invention and Technological Enthusiasm, 1870-1970. The University of Chicago Press, Chicago and London.

Intergovernmental Panel on Climate Change, 2014. Climate Change 2014: Synthesis Report. Available online:. . http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf.

International Telecommunication Union (ITU), 2015. Measuring the Information Society Report. Available online:. . http://www.itu.int/en/ITU-D/Statistics/Documents/publications/misr2015/MISR2015-w5.pdf.

Jessop, B., 1992. fordism and Post-fordism: a critical reformulation. In: Scott, A.J., Storper, M.J. (Eds.), Pathways to Regionalism and Industrial Development. Routledge, London, pp. 43–65.

Kaplinsky, R., 2011. Schumacher meets Schumpeter: appropriate technology below the radar. Res. Policy 40 (2), 193–203.

Kranzberg, M., 1986. Technology and History: “Kranzberg's Laws”. Technol. Cult. 27 (3), 544–560.

Krausmann, F., Gaugl, B., West, J., Schandl, H., 2016. The metabolic transition of a planned economy: material flows in the USSR and the Russian Federation 1900 to 2010. Ecol. Econ. 124, 76–85.

LaFreniere, G.F., 2007. The Decline of Nature: Environmental History and the Western Worldview. Academica Press, Bethesda, Dublin & London.

Lamba, H.S., 2010. Understanding the ideological roots of our global crises: a pre-requisite for radical change. Futures 42 (10), 1079–1087.

Latour, B., 1993. We Have Never Been Modern. Harvard University Press, Cambridge.

Ling, P.J., 1992. America and the Automobile: Technology, Reform and Social Change, 1893-1923. Manchester University Press, Manchester & New York.

Lintsen, H.W., Veraart, F., Smits, J.P., Grin, J., 2018. Well-being and Sustainability in The Netherlands, 1850-2050. Springer International Publishers.

Luhmann, N., 1995. Social Systems. Stanford University Press, Stanford, CA.

Lutz, C., 2014. The U.S. Car colossus and the production of inequality. Am. Ethnol. 41 (2), 232–245.

Magee, C.L., Devezas, T.C., 2017. A simple extension of dematerialization theory: incorporation of technical progress and the rebound effect. Technol. Forecast. Soc. Change 117, 196–205.

Mann, M. 1986/1993/2012/2013. The Sources of Social Power, 4 volumes. Cambridge: Cambridge University Press.

Mathews, J.A., 2014. Greening of Capitalism: How Asia Is Driving the Next Great Transformation. Stanford University Press, Stanford, CA.

Mazoyer, M., Roudart, L., 2006. New York. A History of World Agriculture: From the Neolithic Age to the Current Crisis. Monthly Review Press.

McClellan III, J.E., Dorn, H., 2015. Science and Technology in World History: An Introduction, 3rd edition. Johns Hopkins University Press, Baltimore, MD.

McNeill, J.R., McNeill, W.H., 2003. The Human Web: A Bird's-Eye View of World History. W.W. Norton, New York.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W., 1972. The Limits to Growth: A Report for Club of Rome's Project on the Predicament of Mankind. Universe Books, New York.

Misa, T.J., Brey, P., Feenberg, A. (Eds.), 2003. Modernity and Technology. The MIT Press, Cambridge, MA.
Mokyr, J., 1990. The Lever of Riches: Technological Creativity and Economic Progress. Oxford University Press, Oxford.
Mokyr, J., 2017. Culture of Growth: The Origins of the Modern Economy. Princeton University Press, Princeton, NJ.
Moore, J.W., 2015. London. Capitalism in the Web of Life: Ecology and the Accumulation of Capital. Verso Books.
Nelson, R.R., Winter, S.G., 1982. An Evolutionary Theory of Economic Change. Belknap Press of Harvard University Press, Cambridge, MA & London.
Nye, D.E., 2006. Technology Matters: Questions to Live With. The MIT Press, Cambridge, MA.
Nye, D.E., 2013. America's Assembly Line. The MIT Press, Cambridge, MA.
Østby, G., 2008. Polarization, inequalities and violent civil conflict. J. Peace Res. 45 (2), 143–162.
Ohnmacht, T., Maksim, H., Bergman, M.M. (Eds.), 2009. Mobilities and Inequality. Routledge, London & New York.
Parsons, T., 1951. The Social System. Free Press, New York.
Penn, D.J., 2003. The evolutionary roots of our environmental problems: toward a darwinian ecology. Q. Rev. Biol. 78 (3), 275–301.
Perez, C., 1983. Structural change and assimilation of new technologies in the economic and social systems. Futures 15 (5), 357–375.
Perez, C., 2002. Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages. Edward Elgar, Cheltenham, UK.
Perrow, C., 1984. Normal Accidents. Living With High-risk Technologies. Basic Books, New York.
Piketty, T., 2014. Capital in the 21st Century. Belknap Press of Harvard University Press, Cambridge, MA.
Piore, M.J., Sabel, C.F., 1984. The Second Industrial Divide: Possibilities for Prosperity. Basic Books, New York.
Polanyi, K., 2001. 1944]. The Great Transformation: The Political and Economic Origins of Our Time. Beacon Press, Boston, MA.
Rip, A., Kemp, R., 1998. Technological change. In: Rayner, S., Malone, E.L. (Eds.), Human Choice and Climate Change. Battelle Press, Columbus, OH, pp. 327–399.
Sabel, C.F., Zeitlin, J., 1985. Historical alternatives to mass production: politics, markets and technology in nineteenth-century industrialization. Past Present 108 (1), 133–176.
Sabel, C.F., Zeitlin, J. (Eds.), 1997. World of Possibilities: Flexibility and Mass Production in Western Industrialization. Cambridge University Press, Cambridge.
Sanderson, S.K., 2005. World-Systems Analysis after Thirty Years: Should it Rest in Peace? Int. J. Comp. Sociol. 46 (3), 179–213.
Scheidel, W., 2017. The Great Leveler: Violence and the History of Inequality From the Stone Age to the Twenty-first Century. Princeton University Press, Princeton, NJ.
Schot, J., 2016. Confronting the second deep transition through the historical imagination. Technol. Cult. 57 (2), 445–456.
Schot, J., Kanger, L., 2018. Deep transitions: emergence, acceleration, stabilization and directionality. Res. Policy. https://doi.org/10.1016/j.respol.2018.03.009.
Schot, J., Steinmueller, W.E., 2018. Three frames for innovation policy: R&D, systems of innovation and transformative change. Res. Policy forthcoming.
Schumacher, F., 1973. London. Small Is Beautiful. Blond and Briggs.
Scranton, P., 1997. Endless Novelty: Specialty Production and American Industrialization, 1865-1925. Princeton University Press, Princeton.
Sheller, M., 2015. Racialized mobility transitions in Philadelphia: connecting urban sustainability and transport justice. City Soc. 27 (1), 70–91.
Stearns, P.N., 2013. The Industrial Revolution in World History, 4th edition. Westview Press, Boulder, CO.
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223), 736–746.
Stern, P.C., 2014. Individual and household interactions with energy systems: toward integrated understanding. Energy Res. Soc. Sci. 1, 41–48.
Stiglitz, J.E., 2012. The Price of Inequality. Allen Lane, London.
Sveiby, K.-E., Gripenberg, B., Segercrantz, B., 2012. Challenging the Innovation Paradigm. Routledge, New York.
Swilling, M., Annecke, E., 2012. Just Transitions: Explorations of Sustainability in an Unfair World. United Nations University Press, Tokyo.
Swilling, M., Musango, J., Wakeford, J., 2016. Developmental states and sustainability transitions: prospects of a just transition in South Africa. J. Environ. Policy Plan. 18 (5), 650–672.
Tainter, J.A., 1988. The Collapse of Complex Societies. Cambridge University Press, Cambridge, UK.
Tenner, E., 1997. Why Things Bite Back: Technology and the Revenge of Unintended Consequences. Vintage Books, New York.
Tolliday, S. (Ed.), 1998. The Rise and Fall of Mass Production, vol. 2 Edward Elgar, Cheltenham, UK.
United Nations. 25.09.2015. Transforming our world: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly. Available online: http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.
Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28 (12), 817–830.
Van der Vleuten, E., 2018. Radical change and deep transitions: lessons from Europe's Infrastructure transition 1815-2015. Environ. Innov. Soc. Transit. https://doi.org/10.1016/j.eist.2017.12.004.
Van Deursen, A.J.A.M., Helsper, E.J., 2015. The third-level digital divide: who benefits most from being online? Emerald Studies in Media and Communication. Digital Distinctions and Inequalities 10, 29–53.
Van Deursen, A.J.A.M., van Dijk, J.A.G.M., 2014. The digital divide shifts to differences in usage. New Media Soc. 16 (3), 507–526.
Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., Demeester, P., 2014. Trends in worldwide ICT consumption from 2007 to 2012. Comput. Commun. 50, 64–76.
Wallerstein, I., 1989. The Modern World System III: The Second Era of Great Expansion of the Capitalist World-economy, 1730-1840s. Academic Press, New York.
Waters, M., 1996. Daniel Bell. Routledge, London.
Webster, F., 2015. Theories of the Information Society, 4th edition. Routledge, London.
Wei, L., Hindman, D.B., 2011. Does the digital divide matter more? Comparing the effects of new media and old media use on the education-based knowledge gap. Mass Commun. Soc. 14 (2), 216–235.
Whitehead, A.N., 1925. New York. Science and the Modern World. Macmillan Company.
Winston, B., 1998. Media Technology and Society. A History: From the Telegraph to the Internet. Routledge, London.
Wood, S., 1993. The japanization of fordism. Econ. Ind. Democr. 14 (4), 535–555.