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Deep Transitions: Emergence, Acceleration, Stabilization and Directionality[1]

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Abstract
The unfolding of industrial modernity has led to high levels of wealth and welfare in the Western world but also to increasing global ecological degradation and social inequality. The routine mode of operation of a wide range of socio-technical systems, forming the material backbone of contemporary societies, has substantially contributed to these outcomes. This paper proposes that all these systems can be seen as a surface expression of fundamental meta-rules that for the past 250 years have driven the evolution of these systems and system innovation towards particular directions, thereby constituting the First Deep Transition. To meet the accumulated social and ecological challenges would therefore require a radical change not only in socio-technical systems but also in meta-rules underlying their functioning – the Second Deep Transition. This paper develops a new theoretical framework aiming to explain the emergence, acceleration, stabilization and directionality of Deep Transitions. It does so through the synthesis of three strands of literature: individual socio-technical systems, interconnected systems and industrialization-related macro-trends.

Keywords
Sustainability transitions, long-term change, socio-technical systems, industrial modernity

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1. Introduction

Innovative social science thinking is needed to address the current interconnected social, economic and ecological challenges facing humanity. The core challenge is guaranteeing a humane quality of life for nearly 10 billion people on the planet by 2050 (UN DESA, 2015). Supranational organizations, governments, businesses, NGO-s and other actors need to collaborate in order to secure the provision of sufficient amount of food, affordable and secure energy services, and access to clean water, whilst mitigating the most severe impacts of climate change and adapting to those impacts that will occur (IPCC, 2014). From this perspective, it is clear that the current paradigm of industrial mass production and individualized mass consumption based on intensive use of fossil fuels and a production of a massive amount of waste cannot be extended to all of the world's

[1] This paper has benefited from various conversations, discussions and debates – sometimes more, sometimes less critical, sometimes written, sometimes oral, but always productive, inspiring and encouraging – with a number of people. Special thanks go to Adrian Smith, Cian O'Donovan, Jonas Torrens, Tim Foxon, Frank Geels, Carlota Perez, Andy Stirling, Ed Steinmueller, Frans Berkhout, Koen Frenken, Benjamin Sovacool, Raphael Kaplinsky, Ben Martin, Ralitsa Hiteva, Florian Kern, Daniele Rotolo, Frederique Lang and Caitriona McLeish. We look forward to working with all these people to test the framework.

population without exceeding Earth's planetary boundaries (Meadows et al., 2004; Bardi, 2011; Steffen et al., 2015). There is a second challenge, however. Despite continuing economic growth in many parts of the world, many people still live in poverty. Rising inequalities are resulting in highly uneven distribution of the benefits and costs of growth and development. If high enough, these inequalities may start to undermine the values on which democratic societies are based (Stiglitz, 2012; Piketty, 2014).

Many international organizations, business-linked foundations and official government advisors have responded to this double challenge of environmental change and social inequality. Recently the United Nations (2015) has formulated 17 Sustainable Development Goals (SDGs), calling for revolutionary greener production, increased social justice, fairer distribution of welfare, sustainable consumption patterns and new ways of producing economic growth. Other major organizations are promoting 'inclusive green growth' (World Bank, 2012), 'smart, sustainable and inclusive growth' (European Commission, 2010), 'a circular economy' (European Environmental Agency, 2016) or 'a social contract for sustainability' (WGBU, 2011). However, it remains an open question how these goals are to be achieved.

In this paper we assume that to deliver on the 17 SDGs and similar aims will require a Deep Transition, similar in scale and complexity to that which gave rise to modern industrial systems. We, therefore, distinguish between the First and Second Deep Transition, where the former refers to the rise of industrial modernity, while the latter refers to its fundamental re-ordering (Schot, 2016). We suggest that this sea-change in industrial modernity has gradually started to unfold since the 1970s in specific technological and regional niches, not as a mainstream development but rather as an undercurrent of historical change, to tackle the persistent 'wicked problems' characteristic of the First Deep Transition. These problems such as climate change (caused by the use of fossil fuels), pollution, enormous waste of resources (caused by the assumptions of limitless supply of resources and limitless capacity to absorb waste), inequality (caused by system innovation mainly aimed at the richer markets) and persistent unemployment (caused by a relentless emphasis on productivity growth) are enabled, generated and sustained by a wide range of dominant socio-technical systems for the provision of energy, mobility, communication, housing, clothing, water, healthcare, materials and food put in place during the First Deep Transition and they cannot be overcome by optimizing current systems. Failures to solve these problems, in turn, will generate more and more political unrest and, if not addressed, increase the potential for social conflict (Østby, 2008; Dixon, 2009; Mildner et al., 2011; Hendrix and Salehyan, 2012).

We thus define Deep Transition as a series of connected individual transitions in a wide range of socio-technical systems. The transition is called deep for three reasons: first, it involves changing a set of deeply embedded meta-rules shared among several socio-technical systems; at present this refers to ones created during the First Deep Transition to industrial modernity. These rules are deeply implicated in the enduring problems generated by the emergence of the industrial modernity. Second, the magnitude of social and technical changes required for a Deep Transition implies that its unfolding entails entering a new phase in the history of industrialization, industrial capitalism and perhaps even modernity as a whole. And third, historical experience of the First Deep Transition suggests that the whole shift might take more than a century to unfold in full. In this paper we therefore explore the following broad research question: **how can we understand the emergence, acceleration, stabilization and directionality of Deep Transitions?**

To answer this question we develop a new conceptual framework able to account for major ruptures as well as underlying continuities in the evolution of socio-technical systems over the past two centuries. We begin from the exploration of two influential frameworks focused on the explanation of major long-term socio-technical shifts: Techno-economic Paradigms (TEP) and the Multi-level Perspective (MLP) (section 2). In sections 3 and 4 we work towards a synthesis of these approaches. This, in turn, leads to the outline of two possible developmental trajectories of the Second Deep Transition, outlined in the final section.

A few disclaimers should be made before proceeding. We clearly want to stress our non-teleological and non-determinist credentials: neither the First nor the Second Deep Transition were or are bound to progress towards a pre-defined end-state. Our only claim is that such a transition will have to address the persistent problems generated by the First Deep Transition: however, this can happen in different ways. There is thus no guarantee that current developments would necessarily lead to the reduction of inequality or addressing climate change in a way many would recognize as sustainable development. And the 'logic' of existing socio-technical systems, however this term may be defined, most certainly does not 'force' a unilinear path to the future. We are simply claiming that Deep Transitions cannot be reduced to social drivers abstracted from their material context: the ongoing interactions between the material and the social are a defining feature of Deep Transitions. Moreover, Deep Transitions have been and will be fundamentally shaped by human agency (see Stirling 2008, 2009, for the notion of directionality and importance of politics of transition), albeit an agency exercised within important socio-material constraints.

Finally, we hasten to point out the tentative nature of the ideas presented here. Rather than a full-fledged theory the following account should be read as an extended adventurous hypothesis. This implies that we hold many elements of our framework, including its foundational assumptions, open to criticism, modification and further testing. We therefore end the paper with the contours of a research program that would need to be addressed if a satisfactory answer to our two main research questions is to be given.

2. Theorizing Deep Transitions

The notion of Deep Transitions developed here entails a focus on large-scale and long-term socio-technical systems change. Existing literature on the topic can be thought of as a story being told on three different levels of aggregation:

1. First is the analysis of how socio-technical systems emerge, grow, mature, decline and how shifts from one system to another take place. In this story the evolution of an individual system (e.g. factory production, urban passenger transport) takes a prominent place although what happens in the system's environment can decisively shape its further development. Large Technical Systems (Hughes, 1983; Nye 1998) and the Multi-level Perspective on socio-technical transitions (Geels, 2005; Grin et al, 2010) would be examples of such approaches.
2. Second is the analysis of multiple socio-technical systems that emerge, grow, interact, mature and decline constituting regular long term historical patterns. In this story the focus is on a set of interrelated systems that, however, might also be shaped by the broader environment in which these systems reside. The Control Revolution thesis (Beniger, 1986), Eras of Technology concept (Misa, 2004) and the Techno-economic Paradigm framework (Freeman and Louça, 2001; Perez, 2002) would be examples of such approaches.
3. Third is the analysis which seeks to identify the general characteristics of industrial modernity to argue that developments in recent decades testify to a decisive break away from it. This story then speaks about industrialization as a general trend, albeit one that may interact with other ones (e.g. the capitalism, individualization, secularization etc.). Giddens's work on modernity and self-identity (1991), the risk society thesis (Beck, 1992) or the network society framework (Castells, 2000-2004) would be examples of such approaches.

Each of these stories has their advantages and disadvantages, enabling to capture some aspects of socio-technical systems change while overlooking others. What is missing from current literature, however, is how these three stories relate to each other. We lack an explanation how the interaction of individual socio-technical systems has time and again led to the emergence of tightly connected synergistic clusters (e.g. the coming together of microprocessors, computers, network technology and media content provision during the last decades) that increasingly constitute the socio-material fabric of our everyday lives. Nor do we have a framework for explaining how path-dependencies between such clusters are built up and sustained over centuries so that it becomes meaningful to talk about industrial modernity as a single phenomenon in the first place. The Deep Transition framework will address these two gaps by attempting to establish explicit connections between the three literatures.

What might this synthesis achieve that existing accounts on long-term change have not? Here one could highlight the fact that long-term change of the past two centuries has often been told as one of sustained economic growth (Vries, 2013), development of political systems and institutions (Acemoglu and Robinson, 2012), political and military competition (Hoffman, 2015) or the emergence of new values, ideologies and ways of looking at the world (Mokyr, 2012). What is distinctive about our approach is its emphasis on the endogenous and co-evolutionary interactions between complexes of socio-technical systems in shaping long-term continuities and the directionality of industrial modernity at large. Such a socio-material focus distinguishes the proposal from economic, political and sociological institutionalist literatures that often tend to treat technological change as an exogenous factor enabling institutional change (Kingston and Caballero, 2009; Brousseau et al., 2011; Jones et al, 2013; but see Nelson, 2005, for an exception). On the other hand, it also makes the approach distinctive from various approaches aiming to uncover implicit structures or macro-processes guiding the behaviour of actors (e.g. Lévi-Strauss, 1963; Wallerstein, 1974-2011) as these tend to focus overly on social structures abstracted from their material context, largely downplaying the causal significance of technologies as a result.

The novelty of the approach also means that it is difficult to simply borrow an existing framework and to apply it straightforwardly: what is needed is a synthesis of existing insights, concepts, and theories. As a starting point we have an explicit preference for theories that satisfy – or which in our opinion show strong potential to be developed further in order to satisfy – criteria in the following six dimensions:

1. Level of abstraction: we aim at a middle-range theory of Deep Transitions, that is, a theory combining a limited number of interrelated concepts for making explicit and (potentially testable) context-dependent propositions about a specific phenomenon. We are not interested in proposing an overarching meta-theoretical framework which, owing to its highly abstract nature, would be relatively immune to empirical revision. The analytical vocabulary of the selected theories should be able to contribute to the middle-range goal.
2. Levels of aggregation: the Deep Transitions framework is about creating connections between developments in individual socio-technical systems, interconnected systems and broader industrialization-related macro-trends. Correspondingly, the choice of literature should reflect this by incorporating insights from all levels.
3. Arrows of causality: the mutual shaping of social and material factors should be an integral part of the theory. Neither of them should be prioritized, either ontologically or methodologically, e.g. by reducing the explanation of Deep Transitions to 'social drivers' or 'technological determinants'. Selected theories should therefore be compatible with this premise.
4. Historical evolution: the aim of the theory should be to detect the patterns and mechanisms of Deep Transitions. We want to go further than simply coining a new concept and identifying its supposedly time-independent characteristics: the idea should be to theorize the emergence, acceleration, stabilization as well as the directionality of Deep Transitions. This also means that the selected theories should be able to account for processes operating over a long term time-scale, more than several decades.
5. Geographical scale: the theory should also be able to explain how and why socio-technical

systems change happens at different spatial locations, how linkages between these locations are created and how this process generates global impacts. The analytical vocabulary of the selected theories should enable to develop multi-scalar explanations.

6. Agency: the focus on big historical patterns always creates a danger that the choices made by different actors disappear from view. This is something we would like to avoid. Hence the theories we work with should also be able to integrate the agency of historical actors, especially the power struggles between different social groups that create long-term outcomes and path-dependencies.

Admittedly, taken together this amounts to a rather restrictive set of conditions few existing approaches can even approximate. We think that of the theories dealing with socio-technical systems change there are at least two suitable candidates we want to bring together: the Techno-economic Paradigm (TEP) framework and the Multi-level Perspective (MLP) on socio-technical transitions. Both are middle-range theories focused on the explanation of long-term patterns of socio-technical change which includes the mutual shaping of actors, technologies and institutions. In the following we provide an overview of their main tenets and shortcomings in order to build a first conceptualization of a Deep Transition. We will then use various literatures from Science, Technology and Innovation Studies, history of technology, macro-history and macro-sociology to relate the synthesis of the two approaches (section 3) to even wider trends (section 4).

2.1 Techno-economic paradigm framework

The Techno-economic Paradigms framework (Freeman and Perez, 1988; Tylecote, 1992; Podobnik, 1999; Freeman and Louça, 2001; Dewick et al., 2004; Drechsler et. al, 2009; Mathews, 2013, 2014), especially as developed by Carlota Perez (2002, 2010, 2011, 2013), focuses on explaining the 'long waves' or the 'Great Surges of Development': successive waves of technological, organizational and institutional rearrangements that historically have resulted in major increases in productivity and product quality, structural changes in production and consumption, and long-term economic growth (Perez, 2002). Each surge evolves from small beginnings in certain sectors and/or regional areas and ends up encompassing the entire economies and societies of leading countries, gradually diffusing to other countries as well. Since the beginning of the Industrial Revolution, there have been five such surges, each lasting about 40-60 years[2].

Each surge has consisted of an important all-pervasive low-cost input, often a source of energy (e.g. coal or oil) or a new material (e.g. plastics), new technologies, products and processes, and new or fundamentally redefined infrastructures (Perez, 2010). Yet the transformative power of the surge is not located in the mere presence and interconnectedness of these elements. The transformation only takes off once they are combined with an appropriate techno-economic paradigm, i.e.

> "…a best practice model made up of a set of all pervasive generic technological and organizational principles, which represents the most effective way of applying a particular technological revolution and using it for modernizing and rejuvenating the whole of the economy. When generally adopted, these principles become the common-sense basis for organizing any activity and for structuring any institution." (Perez, 2002: 17)

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[2] It should be noted that the 'long wave' debate is far from settled with some continuing to contest the existence of these waves in the first place (see Korotayev and Tsirel, 2010; Metz, 2011, for recent contrasting viewpoints). It is unclear though whether this refers to deficiencies in the theory itself or to measurement difficulties (Bernard et al., 2014). We therefore prefer to follow Perez's more qualitatively oriented framework that aims to find patterns in the evolution of five clusters of radical innovations. This approach relaxes the more stringent but also in our view unnecessarily restrictive assumptions underlying the long wave approach: narrow focus on the economic domain, a simplistic belief in the global simultaneity of the waves and search for waves in aggregate variables such as GDP (Perez, 2002: 60). However, in this context it is worth mentioning that a recent analysis of patent grants (Korotayev et al., 2011) detected a considerably clearer wave-like pattern on a global than on a national (USA) level.

In other words, techno-economic paradigms provide a 'meta-routine' for the application of new technologies in a number of industries old and new. Acting as coordinating mechanisms these meta-routines generate interconnections between technologies and industries (Perez, 2011: 14). Table 1 provides a descriptive overview of the main characteristics of all five surges.

The dynamics of techno-economic paradigms stem from two sources: first, the saturation of specific technological opportunities within the framework of an existing paradigm. In other words, over time the combination of technological revolutions underlying each wave and their best practices of application run into diminishing returns. The second results from the difference in ease with which the owners of production and finance capital are able to reorient themselves. Whereas the former are tied to the existing equipment, buildings, knowledge, experience, organization, personnel, external networks of suppliers, distributors and clients, the latter are more flexible and mobile. Thus when the existing surge runs into problems the owners of financial capital are able relocate their investments quicker. The owners of production and financial capital are thus the principal actors in Perez's model (2002). The recurrent criticism that the the "long wave" approach is overly deterministic and lacking agency (Köhler, 2012; Lachman, 2013) thus does not apply to the perezian version making it a promising building block for the theory of Deep Transitions.

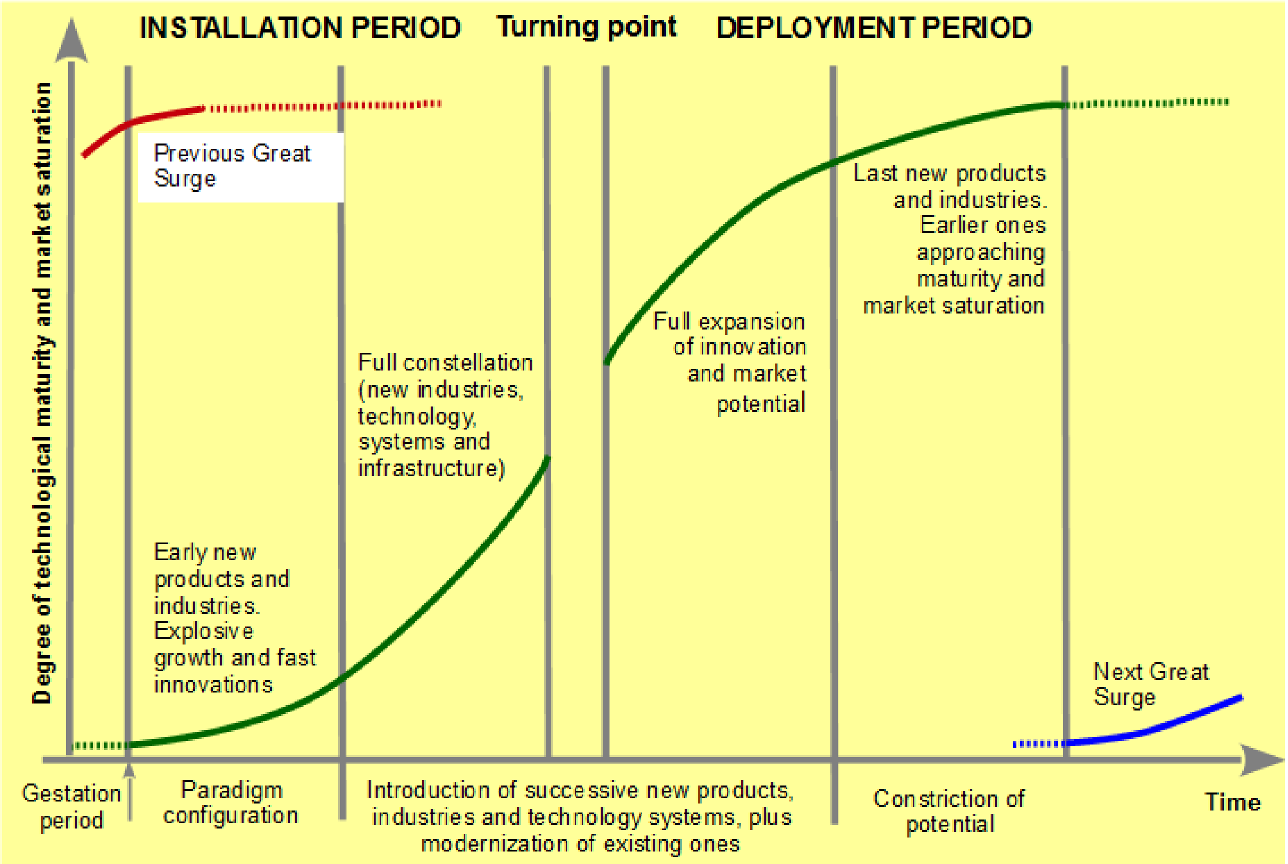
Perez (2002, 2011) divides the evolution of the surges in two periods separated by a turning point: installation period (further divided in irruption and frenzy phases) and deployment (further divided in synergy and maturity phases) (see figure 1). The emergence of each new paradigm overlaps with the decline of the dominant one. In the irruption phase, the old surge starts to exhaust itself which is reflected in declining productivity, increasing unemployment and constricted growth of markets. This prompts the owners of financial capital to find various solutions to this problem: as a result they start to create speculative schemes, invest in new markets and lower cost production sites, but also in new technologies and industries. Early risk-taking investors gain high yields from initial investments leading to generalized but unrealistic profit expectations. In the frenzy phase that follows, massive amounts of capital are directed to emergent industries unable to absorb them. On one hand, these investments enable the creation of new technologies, infrastructures and best practices; on the other hand, they also lead to a speculative bubble and an increasing polarization of rich and poor (Fusari and Reati, 2013). When finally this bubble bursts, a turning point, characterized by serious recession, is reached. This, in turn, generates support for state action and regulatory changes which would create a better institutional environment for the new paradigm while avoiding the excesses of financial speculation. When this happens, the paradigm enters the synergy phase, a golden age, where production capital with long-term expansion strategies takes the lead. What follows is a period of widespread economic growth and decreasing social inequality. During this period, the paradigm acts as a selection mechanism, favouring certain technologies compatible with its logic and rejecting others. In the maturity phase, the potential of the paradigm gradually becomes exhausted creating incentives for financial capital to start looking for more profitable investment opportunities and thereby leading the cycle to repeat itself.

Table 1. Five Great Surges of Development (Perez 2010: 190, 192-193, 196-197).

Technological revolution	Core country or countries	New technologies and new or redefined industries	New or redefined infrastructures	Techno-economic paradigm, 'common-sense' innovation principles
The Industrial Revolution (1771-1828)	Britain	Mechanised cotton industry Wrought iron Machinery	Canals and waterways Turnpike roads Water power (highly improved water wheels)	Factory production Mechanisation Productivity: time keeping and time saving Fluidity of movement (as ideal for machines with water-power and for transport through canals and other waterways) Local networks
Age of Steam and Railways (1829-1874)	Britain (spreading to Europe and USA)	Steam engines and machinery (made in iron, fuelled by coal) Iron and coal mining (now playing central role in growth) Railway construction Rolling stock production Steam power for many industries (including textiles)	Railways (use of steam engine) Universal postal service Telegraph (mainly nationally along railway lines) Great ports, great depots and worldwide sailing ships City gas	Economies of agglomeration Industrial cities National markets Power centres with national networks Scale as progress Standard parts: machine-made machines Energy where needed (steam) Interdependent movement (of machines and of means of transport)
Age of Steel, Electricity and Heavy Engineering (1875-1907)	USA and Germany forging ahead and overtaking Britain	Cheap steel (especially Bessemer) Full development of steam engine for steel ships Heavy chemistry and civil engineering Electrical equipment industry Copper and cables Canned and bottled food Paper and packaging	Worldwide shipping in rapid steel steamships (use of Suez canal) Transcontinental railways (use of cheap steel rails and bolts in standard sizes) Great bridges and tunnels Worldwide telegraph Telephone (mainly nationally) Electrical networks (for illumination and industrial use)	Giant structures (steel) Economies of scale of plant: vertical integration Distributed power for industry (electricity) Science as a productive force Worldwide networks and empires (including cartels) Universal standardisation Cost accounting for control and efficiency Great scale for world market power: 'small' is successful, if local

Age of Oil, the Automobile and Mass Production (1908-1970)	USA (with Germany as vying for world leadership), later spreading to Europe	Mass-produced automobiles Cheap oil and oil fuels Petrochemicals (synthetics) Internal combustion engine for automobiles, transport, tractors, aeroplanes, war tanks and electricity Home electrical appliances Refrigerated and frozen foods	Networks of roads, highways, ports and airports Networks of oil ducts Universal electricity (industry and homes) Worldwide analogue telecommunications (telephone, telex and cablegram), wire and wireless	Mass production/mass markets Economies of scale (product and market volume): horizontal integration Standardisation of products Energy intensity (oil-based) Synthetic materials Functional specialisation: hierarchical pyramids Centralisation: metropolitan centres-suburbanisation National powers, world agreements and confrontations
Age of Information and Telecommunications (1971-...)	USA (spreading to Europe and Asia)	The information revolution Cheap microelectronics Computers, software Telecommunications Control instruments Computer-aided biotechnology and new materials	World digital telecommunications (cable, fibre, optics, radio and satellite Internet/electronic mail and other e-services Multiple source, flexible use, electricity networks High-speed multi-modal physical transport links (by land, air and water)	Information-intensity (microelectronics-based ICT) Decentralised integration: network structures Knowledge as capital: intangible value added Heterogeneity, diversity, adaptability Segmentation of markets: proliferation of niches Economies of scope and specialisation combined with scale Globalisation: interaction between the global and the local Inward and outward cooperation: clusters Instant contact and action: instant global communications

Figure 1. The dynamics of a Great Surge of Development (based on Perez, 2002: 30).



Perez (2013) contends that we are now at the turning point of the fifth surge, which will get its full deployment when information and communication technologies are combined with green growth. She argues that the fifth TEP, enabled by the ICT Revolution, can take the economy in many different directions but only if active institutional innovation creates synergies can the surge succeed in bringing another period of stable long-term growth. In her view, this has historically been achieved by government policy. Tilting the playing field to enable and to encourage massive green innovation radically transforming production patterns and lifestyles on a global scale could do for the world population what the post-war boom did for the West. It would imply a major overhaul of many products and production methods, a redesign of consumption patterns to stress quality, durability, low-energy consumption, low or no emissions, recyclability and upgradeability. Waste management would be handled as a wealth creating process and growth would be decoupled from use of resources.

Although Perez is relaxed about the exact timing of the phases the current surge seems to deviate considerably from the established pattern. If we take 1971 as the starting point of the fifth surge and 60 years as its maximum expected length then the turning point should have been reached about 15 years ago. The dotcom-boom that occurred around the 2000s would indeed fit this pattern. Since then we should have been enjoying the benefits of the golden age, expecting the maturity phase to begin any time soon. What happened instead, of course, were the global financial crisis and a continued increase in social inequality in various developed countries (Piketty, 2014). USA, one of the leading countries of the surge, has experienced a further decline in labour's share of national income (Kristal, 2013) and a polarization of the labour market with jobs in the middle range of the skill distribution being squeezed out (Autor and Dorn, 2013).

There are various explanations to why this might be the case. Perez herself (2013) suggests that the full deployment of the wealth-creating potential of the ICT revolution requires the establishment of adequate socio-institutional frameworks and regulatory frameworks on national as well as international level. According to her argument this has been missing until now because politicians and policy-makers, blinded by the strong neoliberal ideology, have avoided confronting the task of structural reform. In her view turning points could last for years and more than a decade if there is not a major tilting of the playing field by the government (this is what happened during the 1930s when governments refused to manage the economic crisis and for a long time failed to recognize the danger of totalitarian systems). Turning points might also have several bubbles: we have had two during the fifth surge and might be heading towards another one unless governments decide to take adequate action (Perez, 2009). The discussion why this turning point seems to linger on leads us to the question whether instead of moving to a deployment phase of the fifth surge, we might be already moving towards the next one.

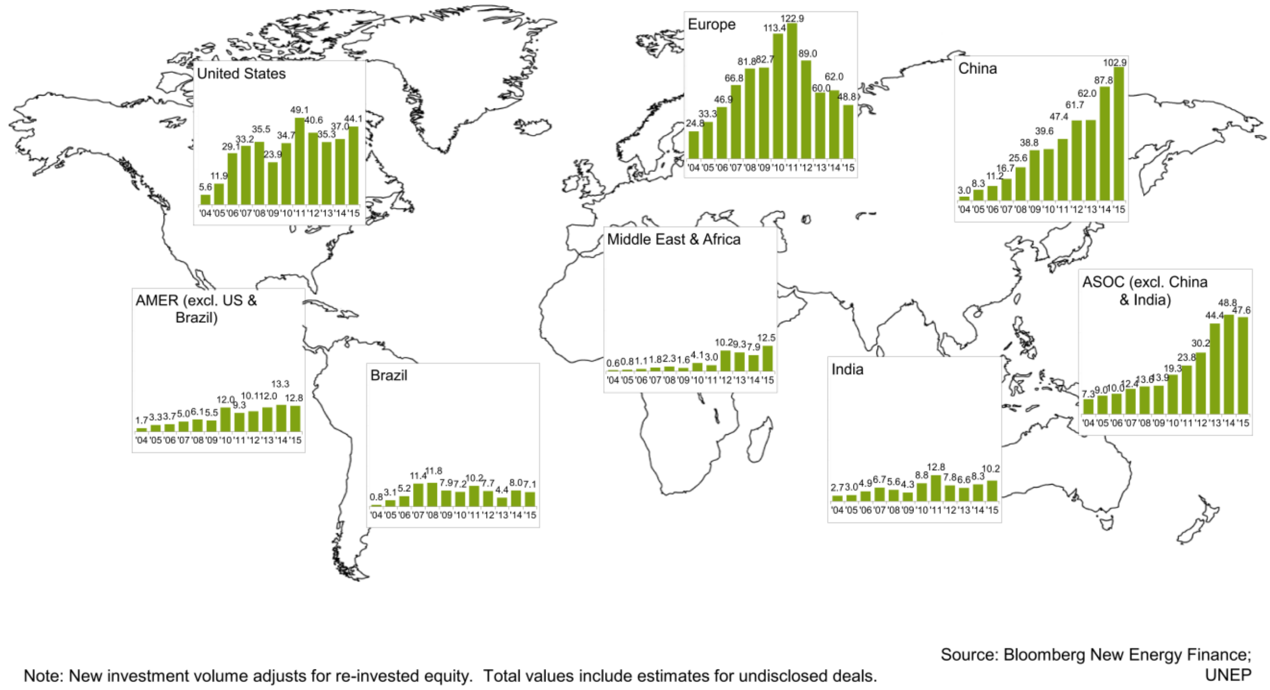
This is what Mathews (2011, 2013) has suggested. He argues that the fifth surge may already be running its course, and hence we may already be experiencing the installation period of the sixth one. This surge is led by China with India, Brazil and Germany also playing an important role. It is characterized by the following features:

- "A shift to renewables as the dominant energy paradigm.
- Decentralized generation of power, from multiple energy sources.
- Competitive international trade in renewable electric power.
- Reduced energy intensity and enhanced efficiency (e.g. through operations of energy services companies).
- Intelligent (smart) IT-enabled grids for distribution of renewable electric power, giving resilience to power networks.
- Biomimetic organizational and industrial design principles (e.g. linked heat and power).
- Circulation of resources and resource efficiency: circular economy.
- Eco-targeted finance." (Mathews, 2013: 17)

Mathews (2014: 106, 158-160) shows that major investments in renewable energy technologies like solar photovoltaic and wind power generation have already occurred resulting in the reduction of production costs, decrease in price and increase in diffusion. However, questions remain about the extent to which it is possible to further scale up the manufacturing and the deployment of these technologies, how to overcome the inertia and political influence of fossil fuel interests, and how to develop appropriate financial instruments to enable institutional investors from pension funds and insurance companies to invest more in renewable and other clean technologies (ibid.). Perez would predict that this first irruption phase should bring huge profits to early investors which will then lead to an investment boom. Hence we would soon expect the investments in renewable energies to develop into a speculative financial bubble. Although investment in renewable technologies is clearly growing all over the world and very rapidly in some regions (see figure 2), the trend does not have the characteristics of a bubble yet. Are we thus really experiencing a sixth surge?

Perez (2013) would argue that investment in renewable energy does not represent a new surge. What we see is renewable development driven by ICT deployment (e.g. smart grids) necessary to make them profitable (Mazzucato and Perez, 2014). As her theory predicts it is at the turning point that the State begins to take action. This is corroborated by the fact that in leading countries of the current surge politicians and policy-makers have realized that the greening of capitalism is necessary to address the challenges of climate change, including massive reductions in waste and pollution production, and have therefore begun to promote it actively (see Mathews and Tan, 2015, for a detailed analysis of China).

Figure 2. Global new investment in renewable energy by region, 2004-2015 ($BN) (Frankfurt School-UNEP Centre/BNEF, 2016: 22).



We suggest that the problematic dating of the fifth surge may imply that it has a markedly different character than the earlier ones, and in fact may represent a transitory period bridging two Deep Transitions. In other words, the turning point of the current surge might simultaneously turn out to be the beginning of a new sequence of Great Surges of Development, the Second Deep Transition. Formulated this way, the TEP framework helps us to conceptualize the historical unfolding of Deep Transitions in various ways. It identifies a recurrent evolutionary pattern during which new technological revolutions and associated best practices emerge, become connected and obtain a specific direction of development in a large number of sectors and areas. Hence TEPs can be seen as the generators of Deep Transitions. They provide both the connections between various socio-technical systems as well as a shared directionality of their development over time. The TEP framework also provides an explanation of the cycle of rise and fall of successive Great Surges of Development. We argue that whereas each surge contributed to the First Deep Transition, it is the five surges taken together that constitute it.

Although the TEP framework provides an innovative conceptualization of the source of interconnections between socio-technical systems and a build-up of their directionality, its account of the dynamics of socio-technical change remains partial. To begin with, while it pays much attention to the actions of the owners of financial and production capital the role of many other social groups is almost completely neglected. For example, TEP does not recognize the active role of consumers and civil-society actors in contributing to the emergence, acceleration and stabilization of surges. Second, although TEP acknowledges the contested nature of new paradigms in which the government plays a central role (e.g. Freeman and Louçã, 2001: 157; Perez, 2011: 27), the politics of all of this are neither explored nor theorized in much detail.

Third, the TEP framework is driven by internal dynamics; the current description seems to have no place for exogenous events such as wars. Perez explicitly argues (2002: 160) that while WWI and WWII accounted for specific features of economic development, they neither influenced the nature of TEPs nor the overall dynamics of their development. They can however accelerate, divert or shape the way a TEP is applied (Perez, personal communication, April 2016). Historical evidence, on the other hand, suggests that wars have had a fundamental impact on the directionality of individual socio-technical systems. For example, one could highlight the effect of WWI on the consolidation of the British electricity system (Hughes, 1983) or on tilting the scales decisively towards the gasoline car in the USA (Mom, 2004). It is hard to see then why the same should not hold for interconnected socio-technical systems and associated meta-routines. In fact, Schot and Rip (2010: 27) have argued that the WWII was a decisive turning point in the Dutch and, in fact, the European debate on how to modernize, helping to establish the dominance of the idea of modernization through scale increase, mass production and mass consumption. Hence we think that the impact of macro-events on TEP development warrants closer attention. However, it must be noted that the category of macro-events does not only include rapid shocks such as wars but also more gradual changes and trends such as climate change, urbanization and globalization.

Fourth, TEP's depiction of paradigm shift follows a substitution pattern: the new paradigm replaces the old one. However, this view omits the existence of a variety of technological, organizational and institutional innovations in specific niches of application. In other words, the decline of one TEP might be accompanied by the simultaneous emergence of not only one but many potentially competing embryonic paradigms. Moreover, historians of technology have shown that old technologies and practices do not disappear: on the contrary they remain vitally important, often continue to persist in specific niches of application, compete against newer technologies, and, in certain conditions, might become popular again (Edgerton, 2007). The area of transport provides several examples: the electric vehicle, bicycle and public transportation have time and again resurfaced (and disappeared) as alternatives for the gasoline car (Mom, 2004; Geels et al., 2012; Longhurst, 2015). A similar dynamic might be at play at the level of TEPs where old technologies and practices continue to exist in parallel with the dominant ones, e.g. the continuation of small shop production in certain sectors and regions even during the heydays of the Fordist mass production regime (Jessop, 1992; Scranton, 1997).

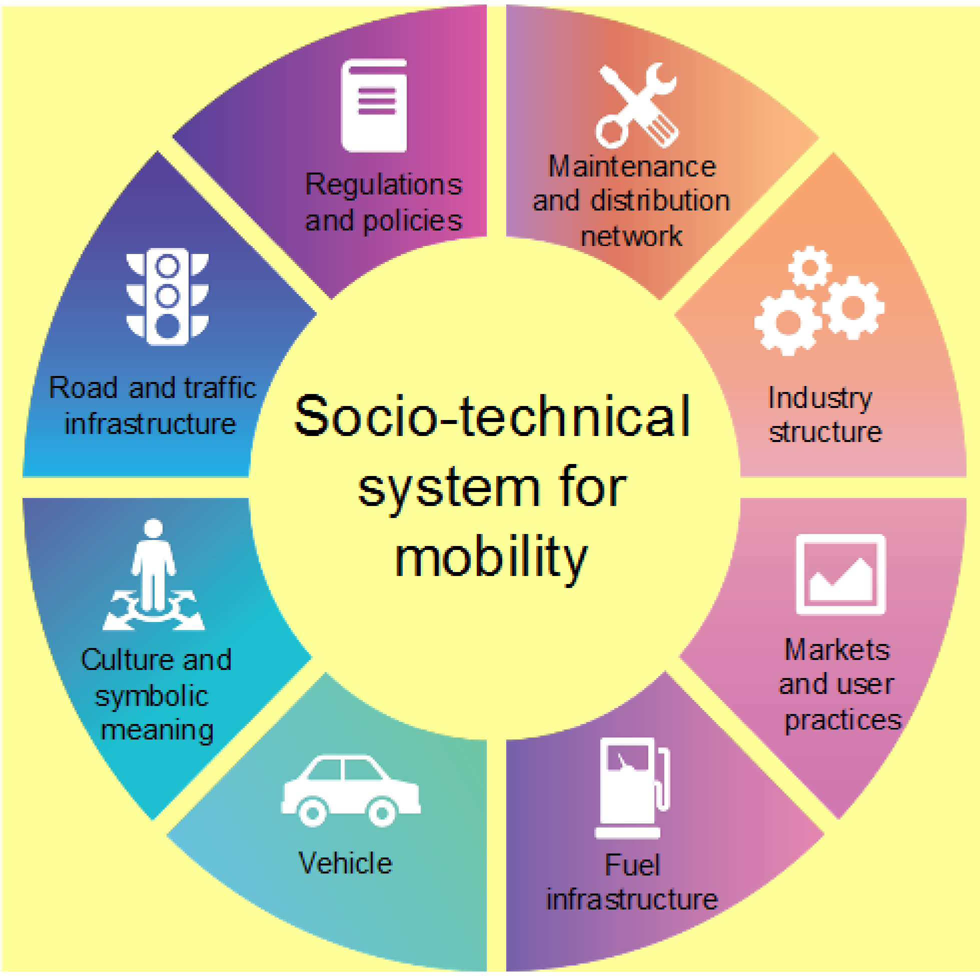
The dynamics between dominant socio-technical systems and niche innovations are at the core of the Multi-level Perspective on socio-technical transitions. It is to this approach that we now turn.

2.2 The Multi-level Perspective

The Multi-level Perspective (Rip and Kemp, 1998; Geels, 2005a; Grin et al., 2010) focuses on explaining large scale and long-term shifts – often 50 years or more – from one socio-technical system to another. Examples of transitions include shifts from horse-drawn carriages to automobiles (Geels, 2005b), from manual to mechanized transshipment in harbors (van Driel and Schot, 2005), from mixed farming to intensive pig husbandry (Geels, 2009), and from fossil fuel based energy system to one based on renewables (Verbong and Geels, 2007).

The basic components making up the multi-level framework are niches, socio-technical regimes and landscape. Socio-technical regimes can be defined as shared, stable and aligned sets of rules or routines directing the behaviour of actors on how to produce, regulate and use transportation, communication, food, and energy technologies. These rules are embedded in the various elements of the socio-technical system and they shape innovative activities towards a specific trajectory of incremental innovation (e.g. increased processing speed in computers or increased fuel efficiency for cars). Figure 3 provides an example of a socio-technical system for land-based transportation.

Figure 3. Socio-technical system for mobility (adapted from Geels 2005b: 446).



New socio-technical regimes are developed in spaces called niches. These are application areas dominated by specific selection criteria which shield the emerging new and unstable technologies from direct market pressure. Compared to dominant regimes the actors in niches are few, their interrelations sparse, the focal technology immature and the guiding rules in constant flux. Niche technologies can then be seen as 'hopeful monstrosities' (Mokyr, 1990): promising in potential, meagre in performance. For this reason niche technologies often need to be protected from pressures exerted by the incumbent socio-technical regimes until they have become mature enough to enter the market.

The concept of landscape refers to the exogenous environment shaping both niches and regimes. Landscape pressures involve trends such as globalization, urbanization and climate change, but also events such as wars, natural disasters, and economic crises. This varied set of factors can be combined in a single 'landscape' category, because they form an external context that niche and regime actors cannot influence – at least in the short run.

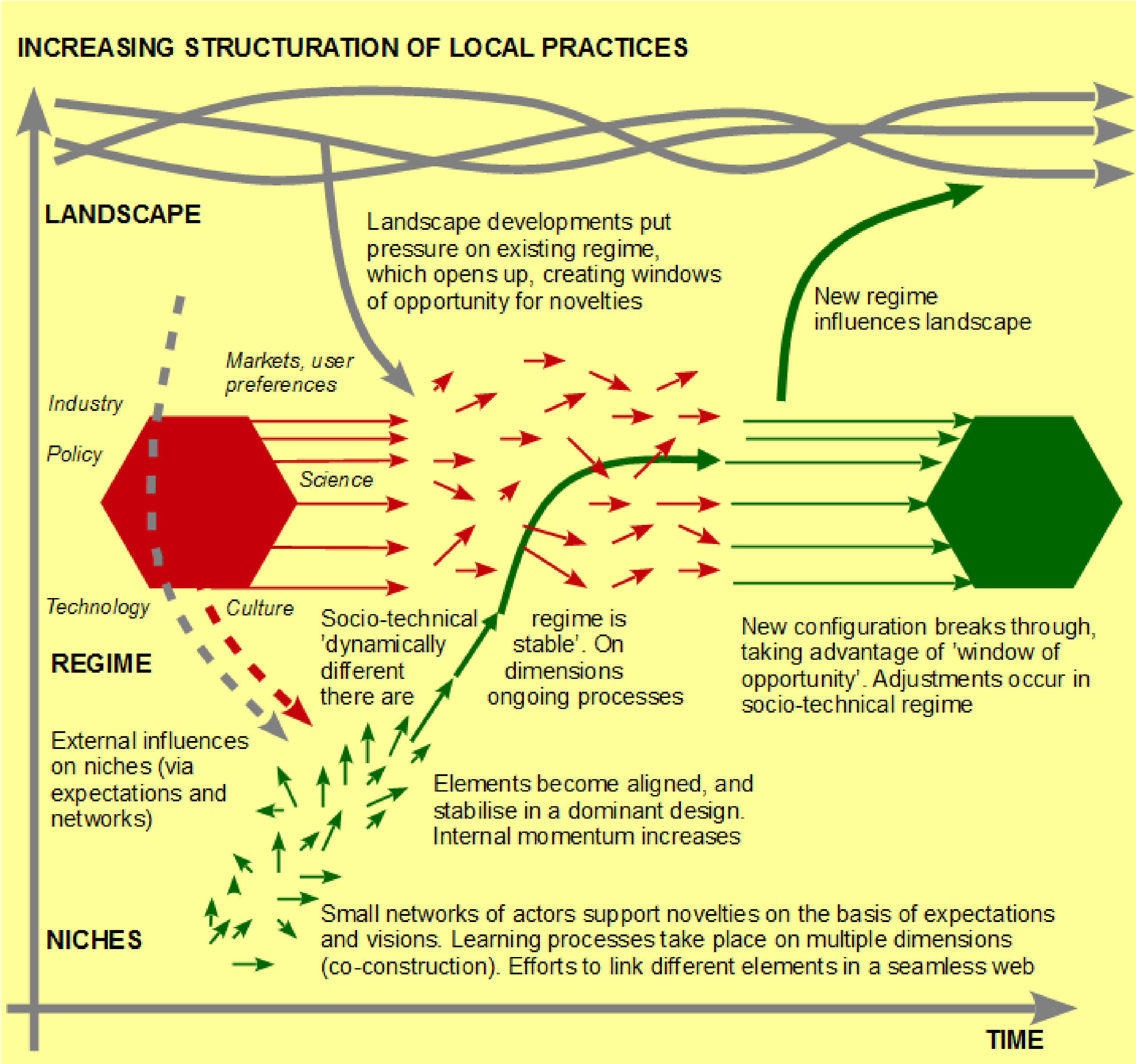
The most important novel insight of MLP is that a transition of a socio-technical system results from the interaction of events on all three levels. A transition typically proceeds in three phases. In the first, start-up phase, landscape pressure exacerbates the internal problems of the regime creating a window of opportunity for niche technologies. For example, in the second half of the 19th century increasing urbanization intensified the problems with horse-drawn carriage regime, including the high cost and low speed of horses or the amount of manure in the streets, facilitating the emergence of niche technologies such as bicycles, trams and automobiles (McShane, 1994; Geels, 2005b). In the second, acceleration phase, niches expand, attract more users, and become mainstream markets starting to compete with the incumbent regime and other niches for dominance. As new technologies diffuse the accompanying rule-sets are redefined. In the case of urban transport transition horse-drawn carriages, bicycles, electric trams, stream trams, electric cars, steam cars and gasoline cars all came to compete against each other for decades until the automobile regime finally established itself as a dominant one (ibid.). In the third, stabilization phase, the number of actors is high, the technology itself mature and the guiding rules relatively stable meaning that the former niche has established itself as a new regime. This allows for a sharp increase in adoption as the regime now provides a ready-made 'template' for largely routinized user behaviour. For example, the dominant practices of car use in the USA had been defined by interwar users whereas the post-war adoption, while much extensive in terms of the number of adopters, was largely based on imitative learning (Kanger and Schot, forthcoming).

One of the key findings of MLP is that transitions can occur through various pathways, depending on the intensity of landscape pressure, the resilience of the dominant regime and the maturity of the niches (Geels and Schot, 2007, 2010). For example, if landscape pressure is relatively intense whereas the niche technologies have not matured enough intense competition between various solutions follows – this is what happened in the case of US urban transport transition. However, if niche technologies are mature a relatively quick technological substitution might follow as evidenced in the shift from sailing ships to steamers (Geels, 2002; see figure 4). Conversely, the lack of sufficient landscape pressure or a high degree of regime resilience may result in no transition or a failed transition (Geels and Schot, 2007, 2010; Wells and Nieuwenhuis, 2012). The MLP thus provides a nuanced analytical vocabulary for explaining not only whether transitions occur but how they do so in individual socio-technical systems.

The early version of MLP was criticized for downplaying agency, for turning insufficient attention to the contested nature of transitions and a failure to capture the influence of specific social groups such as users and cities in shaping transitions (Meadowcroft, 2005; Smith et al., 2005; Smith and Stirling, 2007; Genus and Coles, 2008; Hodson and Marvin, 2010). These issues were taken up in subsequent studies (van Driel and Schot, 2005; Geels, 2006; Elzen et al., 2011; Baker et al., 2014). The resulting additions to MLP have made it clear that the process of transition is far from a moderate and rational consensus-oriented debate about best solutions to clearly defined problems: instead it is rife with struggles between regime-actors and niche-actors with conflicting interests, differing time-scales, problem definitions and perceived best courses of action.

We argue that there are various ways in which MLP's vocabulary can complement the TEP framework as outlined in the previous section. First, the MLP framework includes a richer selection of actors: niches and regimes are shaped not only by the owners of financial and production capital but also by scientists, engineers, policy-makers, users, media, and social movements and so on. Second, MLP not only recognizes the contestation and conflict involved in regime shift but has also made some preliminary steps to theorize the process (see Geels, 2014; Penna and Geels, 2012; 2015) – although whether these insights can be transferred to research on paradigm shifts remains an open issue. Third, although MLP has been criticized for treating landscape as a residual category (Markard and Truffer, 2008; see a response in Geels, 2011) then compared to TEP it provides some analytical vocabulary for conceptualizing the impact of macro-trends and events on the evolution of individual socio-technical systems. And fourth, MLP remains much more sensitive to the issue of variety as preserved in niches. Therefore, in contrast to TEP which assumes a more straightforward process of paradigm substitution, MLP would look for the appearance/disappearance of and competition between the variety of possible paradigms during each shift.

Figure 4. Multi-level Perspective on socio-technical transitions: technological substitution pathway (Geels and Schot, 2007: 401).



However, when it comes to its applicability for the study of Deep Transitions MLP continues to suffer from two important shortcomings. First, a large majority of MLP has focused on transitions involving individual socio-technical systems. In comparison, only a few studies have explicitly explored interactions between multiple regimes. Geels (2007) found that the changing relations between radio and recording regimes – from competitive to symbiotic – contributed to the rise of a music style which can be interpreted as a new combined regime (rock and roll). Raven and Verbong (2009) added two other types of interaction, integration and spill-over. Papachristos et al. (2013) argued that multi-regime interactions (disruptive or reinforcing) might influence the niche formation process through enabling niche transfer, interference or the emergence of a new niche. While all these focused on the possible outcomes of multi-regime interaction Konrad et al. (2008) identified two ways in which these connections are established: functional and structural couplings. The former refer to input-output relationships such as supplier-buyer relationships or global value chains. Structural couplings refer to shared use of infrastructures, actors and rules: for example, telecommunication firms using electricity cables of utilities or both types of companies using the same R&D organization. These findings imply that it is through these couplings that *ad-hoc* multi-regime dynamics become gradually consolidated and eventually stabilized. However, in our final assessment MLP currently does not offer detailed understanding of how the creation of these couplings between different regimes adds up to meta-regimes or new techno-economic paradigms.

The second weakness is shared by MLP and TEP. Namely, at the heart of both approaches is a concern with temporal developments, while the spatial scale of transitions and surges is not explicitly conceptualized. In MLP analyses the three levels are often implicitly conflated with specific territorial boundaries: regimes tend to be studied on the national level, niches on the local or regional level and landscape on the international or global level. The TEP framework, in turn, assumes that paradigms emerge in national contexts, in particular in leading countries. This focus on the national is not inherent to the frameworks, however. The elements of surges can emerge in several countries simultaneously and circulate between multiple locations. Similarly in MLP each level could have a variety of spatial positionings. That is, niches can exist across national borders and regimes can operate in local, national and international spaces. Geographers have made a number of contributions to develop the spatial dimension of MLP further, in particular, by pointing at the importance of exploring the specificities of spaces in which niches, regimes and landscape operate and the need to explore how these spaces link up across local and national borders (Coenen et al., 2012; Raven et al., 2012; Hansen and Coenen, 2015; Truffer et al., 2015). This approach opens up various interesting research possibilities: for example, how global landscape trends or emerging techno-economic paradigms are 'filtered' through particular national constituencies leading to different 'varieties of paradigms' in particular countries. However, as the exploration of the spatial dimensions of MLP is a relatively recent development these observations currently tend to have a sensitizing value and their true explanatory potential remains to be tapped.

We have already introduced the notion of structural and functional coupling as a possible way of establishing links between regimes, usually in particular spatial locations (e.g. the nation state). Yet there has been little mention about the actors involved in this process. Here we would highlight the role of international and transnational organizations which are responsible for developing standards, facilitating mutual learning and providing training and development (Kaiser and Schot, 2014). By aggregating the lessons learned in different countries and acting as international intermediaries these organizations can become dedicated TEP builders. As such they constitute an important transfer mechanism between states and nationally bounded organizations as well as an arena for discussing and negotiating the directionality of transitions. The study of these international and transnational actors can thus help to explain how TEPs get their direction and develop a specific spatial reach.

2.3 TEP and MLP: A comparison

The foregoing sections have suggested that MLP and TEP provide complementary views on large-scale and long-term socio-technical changes. Table 2 summarizes the similarities and differences between the two approaches.

The table enables to make explicit the conceptual similarities between the basic vocabulary of MLP and TEP. Namely, techno-economic paradigms can be seen as connecting mechanisms between individual socio-technical regimes and between these regimes and the landscape. Being shared by multiple regimes a paradigm can thus be understood as a regime of regimes, that is, a meta-regime. This concept matches Perez's own notion of TEPs as meta-routines (2011: 14).

Table 2. TEP and MLP in comparison.

	TEP	MLP
Unit of analysis	Techno-economic paradigm (meta-routines)	Individual socio-technical regimes
What is explained?	Paradigm shift	Shifts to new socio-technical systems
In terms of what?	Actions of the owners of financial and production capital, state intervention around the turning point	Interaction between incumbent socio-technical regimes, emerging niches (both including a wide range of different types of actors) and exogenous landscape pressures
Conflict and contestation	Conflict and contestation acknowledged (especially around the turning point) but not theorized in detail	Emerging attempts to theorize the conflict and contestation of transitions
Temporal scale	40-60 year long cycles	50+ year long transitions
Exogenous events	Not integral part of the framework	Integral part of the framework
Geographical scale and diffusion	New paradigms gradually diffuse from the core towards more peripheral regions and countries	Increasing sensitivity to the multi-scalar nature of transitions but 'methodological nationalism' still prevalent in actual research
Replacement and sources of variety	Simple substitution: new paradigm replaces the old one	Continuous variety that emerges from and is sustained in niches before and after specific transitions

Furthermore, one can immediately note a theoretical gap between TEP and MLP: on one hand, TEP does not have an explanation of how exactly different technological revolutions and emerging best practices interact in order to lead to the emergence and stabilization of new surges; on the other hand, MLP is also unable to explain how this happens in terms of multi-niche or multi-regime interactions. In effect, what is needed is the disaggregation of TEP and an aggregation of MLP. The following two sections undertake exactly this task to conceptualize the historical evolution of Deep Transitions. Although the affinities between TEP and MLP as well as their potential complementarities have been highlighted before (see Köhler, 2012, for an excellent overview) to date the next step remains to be taken. What we will therefore attempt is a synthesis of TEP and MLP to account for the emergence of meta-regimes, the shaping of the socio-technical landscape by multi-regime dynamics, and for the structuring effect of the evolving landscape and the meta-regime on individual regimes and niches. Moreover, we will also turn attention to an additional aspect that MLP, focused as it is on single systems, and TEP both have neglected so far – the issue of between-surge continuities. It also means that we largely leave aside the issues of scale and power/conflict/contestation which will be treated in more detail in a separate paper.

3. Towards a conceptual framework of Deep Transitions: combining TEP and MLP

Since the following account borrows heavily from the analytical vocabulary of TEP and MLP some conceptual clarification is in order. Table 3 provides an overview of the concepts used below, including a brief formal definition, the place of these concepts in the framework and an empirical example. The rest of this section as well as the following one explore the interrelations between these concepts in more detail.

Table 3. Overview of basic concepts used in the framework.

Concept	Definition	Place in the framework	Example
Niche	Spaces for radical innovation that are protected by specific selection criteria	Sustained sources of variety for innovations; seeds for regime-specific and cross-regime rules	Meat-packing industry niche as one of the precursors for mass production
Regime	Relatively stable and aligned sets of rules directing the behaviour of a set of actors along the trajectory of incremental innovation	Multi-regime interactions lead to the emergence of meta-regimes. Dominant regimes also act as selection environments for niches	Fordist mass production as defined in the automobile industry
Socio-technical system	Configuration of actors, technologies and institutions for fulfilling a certain societal function	Manifestation of regimes which may differ depending on the specific characteristics of the environment (e.g. country-level differences)	A system of individual passenger transport in the post-war USA
Technological revolution	Systems of systems: sets of interrelated radical breakthroughs, forming a major constellation of interdependent technologies (Perez, 2010: 189)	Configurations of socio-technical systems	Microelectronics, computers, network infrastructure and the provision of new media content
Techno-economic paradigm	A set of best practices for the employment of technological revolutions	Meta-regimes: rules shared by a range of regimes. Techno-economic paradigms also act as selection environments for niches and individual regimes	The general logic of mass production as employed by various industries in the postwar era
Great Surge of Development	Combinations of technological revolutions and techno-economic paradigms, leading to major economic and societal impacts	Building blocks for Deep Transitions	The Age of Oil, the Automobile and Mass Production (Perez, 2010)
Landscape	Exogenous events and trends that shape niche-regime dynamics	Individual and interlinked socio-technical systems shape landscape dynamics and become gradually embedded to it. Landscape also functions as a selection environment for niches, regimes and meta-regimes	The amplifying effect of mass production on individualization, leading to the abandoning of collective mobility and energy practices during the 20th century (Schot et al., 2010)
Deep Transition	Series of connected and sustained individual transitions in a wide range of socio-technical systems towards a similar direction	Deep Transitions are manifested in continuities between different surges, they can be seen as general features of industrial modernity	Continuous productivity and efficiency improvements offset by corresponding rises in demand

We begin with a proposition that the gestation and early installation period of a great surge of development is characterized by the parallel emergence of new technologies and associated regimes in several niches of individual socio-technical systems. As landscape pressures destabilize various dominant and established regimes multiple windows of opportunity are created for niches containing the promises of new regimes, and thus also embryonic paradigms-in-the-making. These regime destabilisation and niche formation processes are influenced by a host of actors, including firms, investors, governments, social movements and users. These processes also happen in various local contexts, at variable speed and with variable outcomes. However, experiments with new technologies are not restricted to the leading country. The success of the leading country can be more readily explained by its ability to learn from the experiments conducted in various locations, for example by participating in transnational and international platforms and organizations; to 'borrow' the outcomes (e.g. new technologies, organizational innovations, institutional lessons) and to bring them together in a particular location. In any case, all these niches and emerging regimes provide a raw material, an essential variety from which the future TEP will be constructed.

During the irruption phase the emerging and incumbent regimes come to compete against each other resulting in transitions (or transition failures) – outcomes that can be analysed in conventional MLP terms. Deep conflicts might develop between regime and niche actors, and also between actors promoting different niche-innovations. Through these transitions the future techno-economic paradigm starts to emerge. Its seeds might become dominant in certain individual systems in certain countries or regions, but not in others: for example, mass production techniques may be widely adopted in a chemical industry but not in the fashion industry or agricultural sector. The variety of different options means that at this point the outline of the emergent paradigm still cannot be sketched with any certainty.

This in itself does not explain how certain paradigms become shared across systems though. We therefore propose that towards the end of the irruption and the beginning of the frenzy phase various potential paradigms start to diffuse through multi-regime dynamics. As the owners of financial capital direct investments to new technologies and industries, niche actors speed up the development of new technologies and associated best practices while regime actors begin to doubt whether the dominant systems have a bright future. Again it is important to stress the wide range of possible actors involved including firms, investors, users, social movements, civic groups, cities and various government agencies. Actors related to different expanding niches establish structural and functional couplings between multiple emergent regimes. This process can be further facilitated by the aggregation work of dedicated TEP builders. These actors, often inter- and transnational organizations, bring together experiences and ideas from different sectors, nurture mutual learning processes, help to establish networks between various stakeholders and shape expectations about the future of the niches. As such they build and empower the niches while hollowing out dominant regimes at the same time. In this way different paradigms-in-the-making diffuse to new socio-technical systems (or are sometimes imposed on them as standards, for example through quality accreditation processes). As a result the connections between multiple regimes gradually start to become consolidated. However, at this point many possible paradigms still exist and hence it remains unclear which one would eventually prevail.

This situation is finally resolved at the turning point. Until then there is still a variety of TEPs and hence many possible directions in which the new surge might unfold. However, the bursting of a speculative bubble around new technologies and nascent industries will incentivize the leading countries to create better regulatory conditions. Combined with the eruption of additional landscape pressures – either a rapid shock (such as war) or an accumulation of a longer trend reaching a critical threshold (such as climate change) – the perceptions of various actors become directed towards a similar direction. Therefore, from this point onwards one can start talking about the existence of *the* dominant techno-economic paradigm advanced by leading countries and providing directionality across many socio-technical systems. Other countries then feel forced to play a catch-up game. The alternative paradigms do not disappear entirely though: they may remain regime-specific victories or revert to niche status, waiting to re-emerge at the next suitable opportunity. These niches represent alternative pathways advanced at specific locations, in specific sectors and by dedicated countries. This idea is supported by historical evidence showing that the principles of mechanization, use of science, economies of scale, mass production and mass consumption had to confront principles of batch production, use of tacit knowledge and craft based innovation, flexible specialization and appropriate technology during every surge (Piore and Sabel, 1984; Sabel and Zeitlin, 1985; Scranton, 1997; Schot and van Lente, 2010; Kaplinsky, 2011).

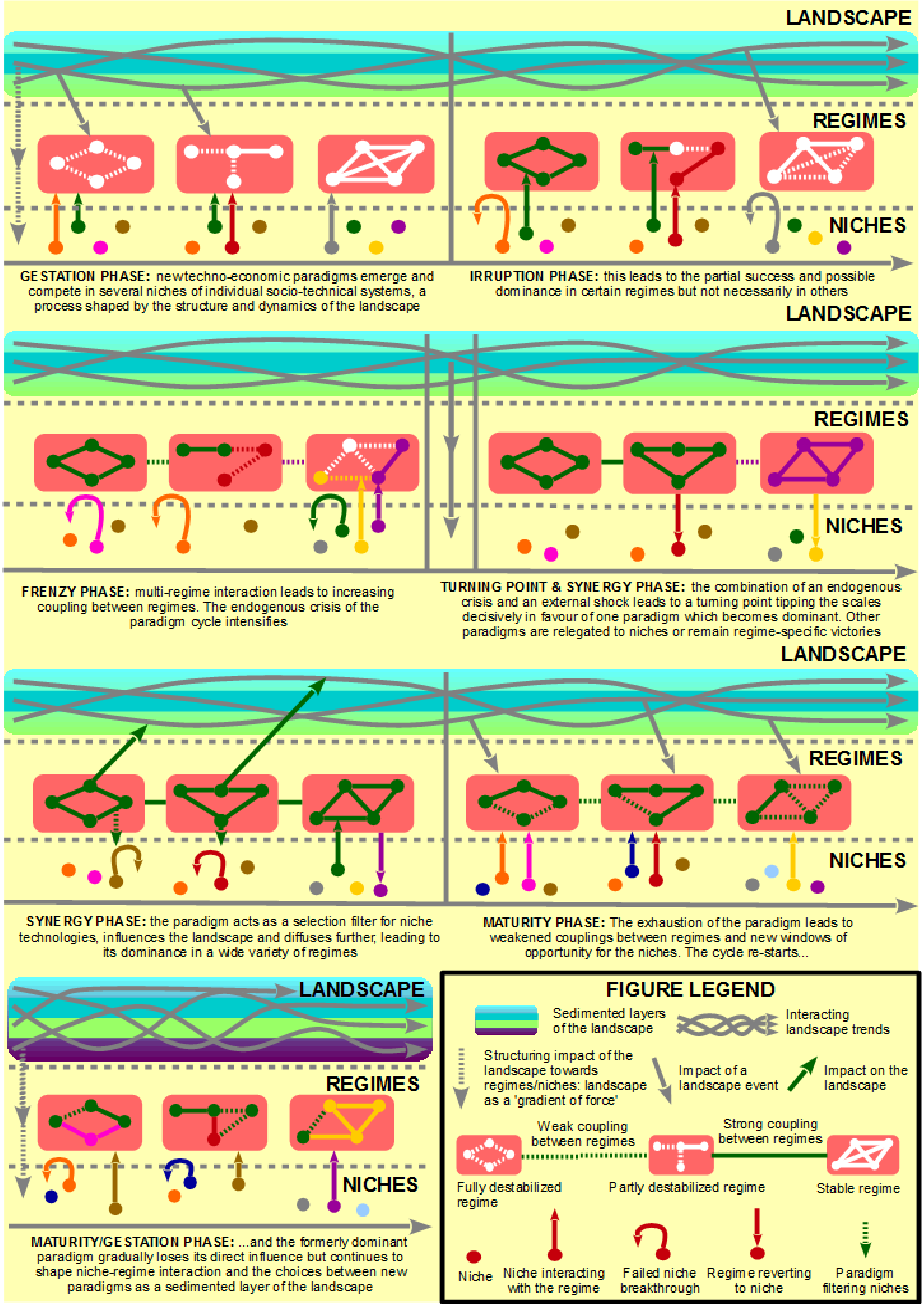
In the synergy phase the dominant paradigm starts to exert its influence in three directions. In relation to niches it acts as a selection mechanism, favouring technologies compatible with its logic and rejecting non-compatible ones (Perez, 2011: 20). In relation to regimes it acts as a meta-regime, leading to the increasing take-up of its principles in various sectors and thus to ever stronger couplings between different regimes. Finally, in this phase wide-scale impacts of the surge on economy and society, many of those totally unforeseen and unintended, occur. In other words, the surge starts to shape landscape trends. An example is individualization which was strongly shaped and reinforced during the 20th century by the emergence of the TEP of mass consumption in a wide range of socio-technical systems. As a result, many alternatives, such as collective mobility, energy, housing, washing and cooking practices were abandoned (Schot et al., 2010).

In the maturity phase the direct structuring effect of the paradigm in relation to regimes and niches is at its maximum. Yet as its potential starts to become exhausted, new problems and opportunities start to appear which cannot be fully pursued by extending the logic of the dominant paradigm. The scene is set then for yet another surge with the owners of financial capital ready to shift their investments. But this loss in visibility and direct impact does not mean that the surge loses its impact altogether. On the contrary, we propose that beginning from the maturity phase the surge gradually becomes embedded in the landscape itself. It becomes to constitute a sedimented layer of the landscape, a set of very deep material and ideological structures, expressed in infrastructures, spatial patterns of urbanization or vast webs of routine everyday practices (Shove, 2003; Edgerton, 2007). This all-encompassing network of old and well-established technologies provides the context in which new niches, regimes and paradigms can emerge, interact and flourish (e.g. digital revolution relying on electrical networks). It also continues to shape long-term landscape trends long after it has ceased to be the primary locus of radical innovative activities and major source of economic growth (e.g. the continuing contribution of the automobile to suburbanization, individualization and pollution). Its high degree of embeddedness and deep-structural nature makes it invisible yet all the more powerful in providing “'gradients of force', that make some actions easier than others” (Geels and Schot, 2007: 403). The whole sequence is summarized in figure 5.

4. Deep Transitions as between-surge continuities

In the previous section we combined the insights of TEP and MLP to provide a more comprehensive explanation of great surges. Although this has brought us closer to understanding the dynamics of Deep Transitions we argue one additional step is needed. We therefore build on the notion of sedimentation introduced in the previous section suggesting that there is a fundamental continuity between surges. In fact, it is this very notion of between-surge continuity that makes it meaningful to speak about the last 200-250 years as an unfolding of a single process what we have called the First Deep Transition.

Figure 5. The multi-level explanation of a Great Surge of Development.

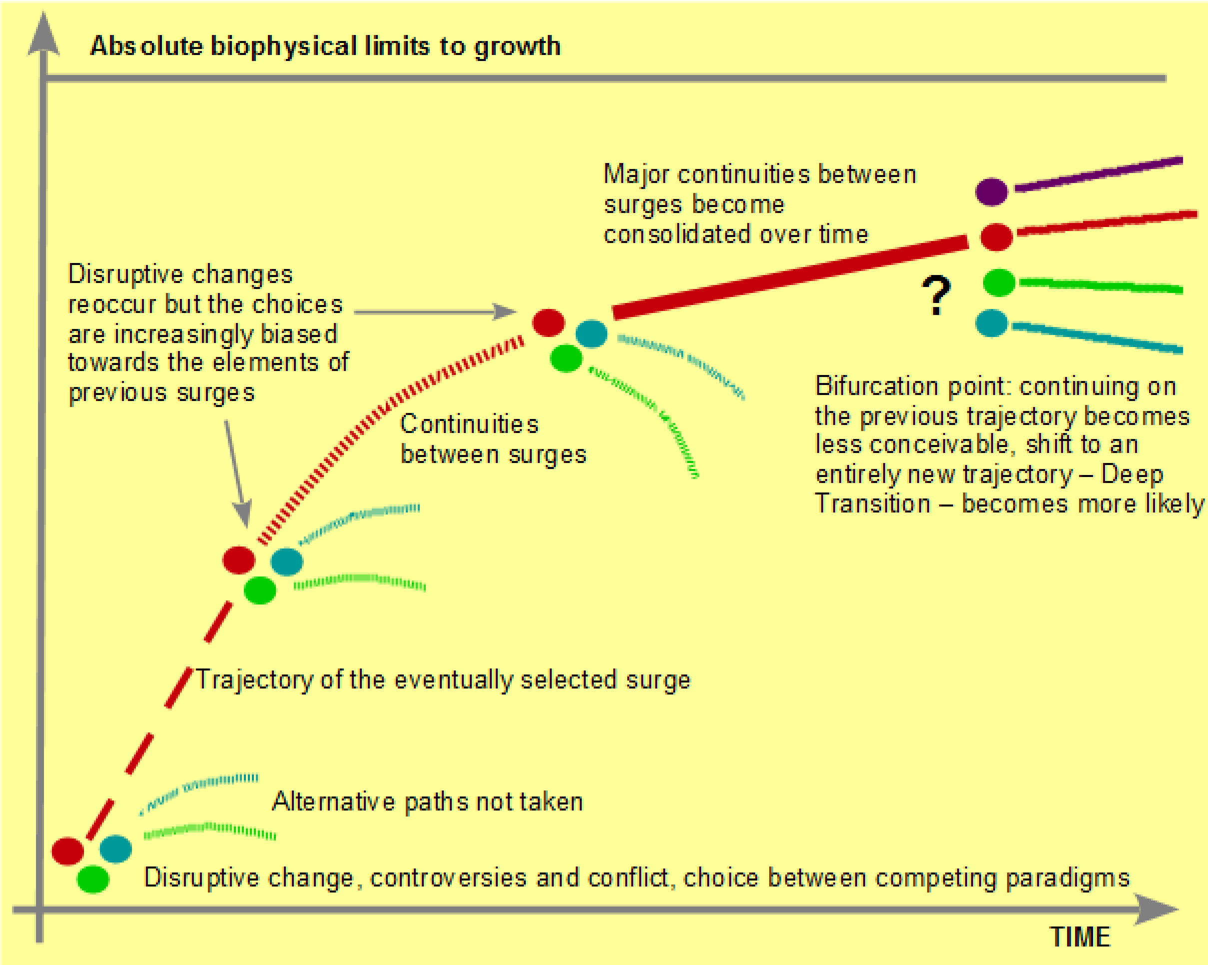


We have not yet compiled a comprehensive list of these continuities. However, based on a survey of literature on macro-level technological and societal changes (Mokyr, 1990; Beck, 1992; Grübler, 2003, Misa et al., 2003; McNeill and McNeill, 2003; Christian, 2004; Arthur, 2009; Lamba, 2010; McClellan and Dorn, 2015; Moore, 2015), we propose a number of similarities shared by each surge to date:

- Increasing resource requirements including:
  - heavy reliance on fossil fuels in maintaining the living standard of modern civilization and an accompanying increase in energy consumption per capita;
  - increasing demand for raw materials, products and infrastructures to satisfy "basic human needs", however defined, of the members of society accompanied by increasing ecological footprint and the production of waste.
- Increasing role of technologies in systems of production and consumption, leading to:
  - productivity and efficiency improvements, which have historically frequently tended to be offset by rises in demand stimulated by these improvements;
  - increasing complexity, variety, capital- and skill-intensity of industrial production and distribution activities;
  - increasing scale, scope and interconnectedness of technological infrastructures underpinning the functioning of modern societies with an accompanying increase in the risks of systemic failure;
  - increasing reliance on various technologies for the "normal" conduct of everyday life.
- Deep-seated attitudes and beliefs about our socio-material environment:
  - instrumental view of nature, including humans, as a resource to be harnessed, controlled and manipulated through the application of science and technology with relatively little (albeit increasing) concerns about the ensuing environmental effects;
  - pervasive use of labour productivity as an adequate metric of efficiency in production (as opposed to resource efficiency), acquisition of ever more goods and services in consumption and preoccupation with economic growth as end and means on the state level as indicators of "societal progress" and "development";
  - a continuing (although increasingly moderated) view of technology as inherently value-free means and a progressive force in history enabling emancipation, empowerment and self-realization;
  - belief in the possibility of endless economic growth, assuming limitless supply of resources (or at least limitless possibilities for finding easy substitutes for scarce ones) as well as limitless capacity to absorb waste.
- Specific relations between science, technology, innovation and governance:
  - a view of basic science and technology as public goods, which will bring economic growth and therefore deserve investment by the State. The results of these investments, however, can be appropriated by the private sector under the rubric of innovation;
  - increasing interconnections between science, technology and innovation, whereby science becomes a direct input to technological research and development activities;
  - a view according to which the developers of new products and systems are generally not to be held responsible for the impacts; these are perceived as negative externalities to be solved by the State through regulation.

This list reflects a specific type of path dependency operating on a scope and time-scale beyond that expressed in the standard technological path-dependence literature (David, 1985; Arthur, 1989; Araujo and Harrison, 2002). Building on this observation we suggest that the trajectory of the First Deep Transition was loosely established during the first surge whereas each following one has complemented but also strengthened and deepened it in particular ways. It follows that – save for the first surge – each time a mature paradigm started to exhaust itself and new ones (re)appeared, the choice between competing paradigms was increasingly biased towards certain options. This happened because of the structuring effect of prior surges which had sedimented, become part of the socio-technical landscape, and hence also part of the selection environment. The eventual outcome, a new surge, then simultaneously meant a notable rupture in comparison to the previous one but also not a complete deviation from the underlying logic of the first Deep Transition. As each new paradigm added weight to the existing trajectory it also made the outcomes of this large transition less and less reversible. This may explain, on one hand, the above observation about the resurgence of the principles of batch production and flexible specialization during every surge but also, on the other hand, why eventually all these principles were applied in a way as to deepen the logic of mass production and mass consumption. Figure 6 visualizes this proposition.

Figure 6. Cumulative effect of Great Surges of Development: A very long term path dependency.



But how can this deepening process through the thickening of the socio-technical landscape then become redirected? At this point we have to introduce a distinction between absolute and relative limits of each surge (and the First Deep Transition as a whole). We acknowledge that absolute biophysical limits to socio-material expansion do exist and that they may ultimately be reached should the current trends continue. The definition of such limits of the possible has been the task of many models of which the 'limits to growth' approach is perhaps the most famous (Meadows et al., 1972, 2004; Turner, 2008; Bardi, 2011). However, despite some rather gloomy forecasts these limits have not been reached throughout the history of industrialization and modernization, and absolute biophysical limits have yet to constrain the First Deep Transition (though it has been argued that human activity has already led to overshooting particular planetary boundaries (Steffen et al., 2015)). Therefore, the existence of these limits by themselves cannot explain why surges occur. What have historically prompted each surge instead are the diminishing returns of each surge, and more recently, the perception of various actors that we are coming close to absolute limits. We thus seem to be dealing here with a notion of 'presumptive anomaly', defined as the assumption that "either that under some future conditions the conventional system will fail (or function badly) or that a radically different paradigm will do a much better job or will do something entirely novel" (Constant, 1980: 15).

It might be helpful to think of each surge as a set of capabilities that can only yield a certain amount of output given the needs and goals of the actors employing it. But these needs and goals are not exogenous to the surge but constructed during its development. In other words, as each surge opens up genuinely new possibilities it also re-defines the limits of the possible: for example, mass production and mass consumption as we know them today were simply impossible to achieve with the technologies and practices of the first surge and hence impossible to formulate by a majority of the population as reasonable expectations. It is only when these expectations become widespread and normalized that the question arises whether the capabilities of the current surge are able to accommodate for these demands without any drop in profitability or any major harmful side-effects. The limits of the surge, used in this sense, then refer to limits relative to the expectations of actors benefiting from it. It is the perceived threat of reaching these limits that has historically led to new surges. In this light the TEP framework can be criticized for focusing on only one specific way in which these relative limits have been perceived – the exhaustion of a dominant paradigm as an incentive for the owners of financial capital to seek new investment opportunities. We suggest broadening this notion by incorporating other types of perceived limits beyond narrowly economic ones, e.g. increasing concerns about the accumulating environmental impacts or concerns about inequality and human welfare as reflected, for example, by the 17 Sustainable Development Goals (UN, 2015).

5. Deep Transitions and the future: bottom-up vs. top-down transformation pathways

At this point our non-teleological and non-determinist credentials are worth repeating: 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. However, if the Second Deep Transition really takes place there are multiple pathways through which it might do so. In this section we explore two possible scenarios called partial internalization and full internalization.

The partial internalization scenario implies the continuation of the currently dominant developmental trajectory of production and consumption aimed at high-income consumers through mass production methods which are capital- and skill-intensive, which aim to reap economies of scale through large-volume production and which 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 and further development of global value chain of 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.

This 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, increased social inequality, resource-related conflicts, recurrent natural disasters and forced migration. Hence in this scenario powerful forces would need to be put in place to prevent and mitigate disasters and conflicts, compensate for social excesses, and underwrite the legitimacy of the system, in order to avoid potentially catastrophic outcomes. Given the high ecological and social costs to absorb, this partial internalization pathway would imply constructing a new relationship between the state, the market, and civil society, and most likely new forms of pro-active and entrepreneurial state action on 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 full internalization strategy would address the double challenge of looming ecological crisis and deepening social inequality in a different way. The exact directionality of this pathway of the Second Deep Transition is impossible to predict at the moment yet based on our tentative analysis of similarities between TEPs we would hazard a few educated guesses. 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 full internalization scenario would require yet another re-invention of the way we innovate.

In this paper we have introduced the notion of Deep Transitions to make sense of the socio-material challenges inherited from the past and confronting us today. We have also discussed how existing frameworks and insights from technology studies could be synthesized for theorizing Deep Transitions. In so doing we have tried to speak to a number of audiences interested in large-scale and long-term socio-technical systems change, including (but not limited to) the fields of Science, Technology and Innovation Studies, sustainability transitions, history of technology and macro-sociology. Admittedly the resulting framework has been speculative but – owing to the novelty of the approach – necessarily so. Hopefully we have achieved our mission of opening up a number of questions to be explored in future research in order to see whether our formulation turns out to be accurate as well as inspiring. Based on the foregoing discussion we would like to conclude the paper with a brief research agenda:

1. Detecting Deep Transitions: the notion of Deep Transitions implies wide-ranging ruptures in technological, organizational and institutional innovation in terms of the speed of innovation as well as the emergence of qualitatively new solutions (the emergence of new “species”, rather than the optimization of the existing ones). At the same time it also hints to the relative durability of various social and material between-surge continuities (see section 4 for our tentative list). The detection and patterning of these ruptures and continuities invites methodological experimentation, e.g. the use of phylogenetic methods (Mesoudi, 2011; Valverde and Solé, 2015), Big Data analytics (Manning, 2013) or scientometric techniques (Rotolo et al., 2015). In particular, a quantitative mapping of patterns in the evolution of rules and meta-rules is a promising research avenue as both MLP and TEP literatures have so far identified regimes and techno-economic paradigms on the basis of qualitative interpretation of historical data, resulting in a certain lack of analytical rigour.
2. Further elaboration of the framework: more conceptual work is needed on the spatial dimension of the surges, on the role of political economy and power conflicts in shaping the surges, on multi-regime and multi-niche dynamics, and on making and breaking links between regimes, surges and the landscape. We further suggest that the overall evolutionary

pattern of development of socio-technical systems might be more accurately captured by the notion of portfolio of directionality which would include both, niches as the sources of sustained variety and meta-regimes that are temporarily dominant in particular places and at particular times. This notion of portfolio of directionality might go a long way in explaining both, the high degree of continuity in long-term socio-technical change as well as occasional rapid discontinuities both characteristic to industrial modernity.

3. Extended analysis of the turning points of the surges (past and present) including the role of wars and other landscape pressures in shaping the direction of change at critical junctions. Of particular interest is the emerging and possibly intensifying clash between the First and the Second Deep Transition.
4. The combined use of qualitative socio-technical scenarios and quantitative modelling (Foxon, 2013; McDowall, 2014) to probe the possible futures of which the Second Deep Transition might be a part. Looking ahead up to 2050 and aiming to capture at least two surges these efforts might focus on the articulation of niches in which new competing TEPs might emerge, on multi-regime dynamics, crises and shocks through which these paradigms might evolve and become to compete, and on processes by which successful TEPs might diffuse and gain dominance in a wider variety of regimes. These scenarios could also explore transnational dynamics or examine how competing paradigms may be adopted in different regions across the world thereby avoiding a Western bias.

The world is in transition and a great deal of the possible outcomes of this transition do not look desirable. The success of intervention ultimately depends on whether the analysts get the problem right. Only then are we as knowledgeable and reflexive actors of the world in a position to make an informed decision about the elements of the present we would like to take with us and the ones we should leave well behind. Only then can we devise strategic actions that cross the gap between where we are and where we want to be. Only then can we ensure that the unfolding of the Second Deep Transition would not wreak havoc on humanity and nature. The authors invite everyone to join them in this intellectual quest.

References

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

Araujo, L., and Harrison, D. 2002. Path Dependence, Agency and Technological Evolution. *Technology Analysis & Strategic Management* 14(1): 5-19.

Arthur, W. B. 1989. Competing technologies, Increasing Returns, and Lock-In by Historical Events. *The Economic Journal* 99(394): 116-131.

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

Autor, D. H., and Dorn, D. 2013. The Growth of Low-Skill Jobs and the Polarization of the US Labor Market. *American Economic Review* 103(5): 1553-1597.

Baker, L., Newell, P., and Phillips, J. 2014. The Political Economy of Energy Transitions: The Case of South Africa. *New Political Economy* 19(6): 791-818.

Bardi, U. 2011. *The Limits to Growth Revisited.* New York: Springer.

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

Beniger, J. R. 1986. *The Control Revolution: Technological and Economic Origins of the Information Society.* Cambridge: Harvard University Press.

Bernard, L., Gevorkyan, A. V., Palley, T. I., and Semmler, W. 2014. Time scales and mechanisms of economic cycles: a review of theories of long waves. *Review of Keynesian Economics* 2(1): 87-107.

Brousseau, E., Garrouste, P., and Raynaud, E. 2011. Institutional changes: Alternative theories and consequences for institutional design. *Journal of Economic Behavior & Organization* 79(1-2): 3-19.

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

Christian, D. 2004. *Maps of Time: An Introduction to Big History.* Berkeley and Los Angeles, CA: University of California Press.

Coenen, L., Benneworth, P., and Truffer, B. 2012. Toward a spatial perspective on sustainability transitions. *Research Policy* 41(6): 968-979.

Constant II, E. W. 1980. *The Origins of the Turbojet Revolution.* Baltimore, MD: Johns Hopkins University Press.

David, P. A. 1985. Clio and the economics of QWERTY. *The American Economic Review* 75(2): 332-337.
Dewick, P., Green, K., and Miozzo, M. 2004. Technological change, industry structure and the environment. *Futures* 36(3): 267-293.
Dixon, J. 2009. What Causes Civil Wars? Integrating Quantitative Research Findings. *International Studies Review* 11(4): 707-735.
Drechsler, W., Kattel, R., and Reinert, E. S. 2009. *Techno-economic paradigms: Essays in honour of Carlota Perez.* London: Anthem Press.
Edgerton, D. 2007. *The Shock of the Old: Technology and Global History Since 1900*. Oxford: Oxford University Press.
Elzen, B., Geels, F. W., Leeuwis, C., and van Mierlo, B. 2011. Normative contestation in transitions 'in the making': Animal welfare concerns and system innovation in pig husbandry. *Research Policy* 40(2): 263-275.
European Commission. 2010. *Europe 2020: A strategy for smart, sustainable and inclusive growth*. COM(2010) 2020 final. Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52010DC2020&from=en.
European Environmental Agency. 2016. *Circular economy in Europe: Developing knowledge base.* Available online: http://www.eea.europa.eu/publications/circular-economy-in-europe/at_download/file.
Foxon, T. J. 2013. Transition pathways for a UK low carbon electricity future. *Energy Policy* 52: 10-24.
Frankfurt School-UNEP Centre/BNEF. 2016. *Global Trends in Renewable Energy Investment.* Available online: http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2016lowres_0.pdf.
Freeman, C., and Louçã, F. 2001. *As Time Goes By: From the Industrial Revolutions to the Information Revolution.* Oxford: Oxford University Press.
Freeman, C., and Perez, C. 1988. Structural crisis of adjustment, business cycles and investment behaviour. In *Technical Change and Economic Theory*, eds. G. Dosi, C. Freeman, R. Nelson, G. Silverberg, L. Soete. London: Frances Pinter, 38-66.
Fusari, A., and Reati, A. 2013. Endogenizing technical change: Uncertainty, profits, entrepreneurship. A long-term view of sectoral dynamics. *Structural Change and Economic Dynamics* 24: 76-100.
Geels, F. W. 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy* 31(8-9): 1257-1274.
Geels, F. W. 2005a. *Technological Transitions and System Innovations: A Co-Evolutionary and Socio-Technical Analysis*. Cheltenham: Edward Elgar.
Geels, F. W. 2005b. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860-1930). *Technology Analysis & Strategic Management* 17(4): 445-476.
Geels, F. W. 2006. The hygienic transition from cesspools to sewer systems (1840–1930): the dynamics of regime transformation. *Research Policy* 35(7): 1069-1082.
Geels, F. W. 2007. Analysing the breakthrough of rock'n'roll (1930-1970): Multi-regime interaction and reconfiguration in the multi-level perspective. *Technological Forecasting & Social Change* 74(8): 1411-1431.
Geels, F. W. 2009. Foundational ontologies and multi-paradigm analysis, applied to the socio-technical transition from mixed farming to intensive pig husbandry (1930-1980). *Technology Analysis & Strategic Management* 21(7): 805-832.
Geels, F. W. 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions* 1(1): 24-40.
Geels, F. W. 2014. Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective. *Theory, Culture & Society* 31(5): 21-40.
Geels, F. W., Kemp, R., Dudley, G., and Lyons, G. (eds). 2012. *Automobility in Transition? A Socio-Technical Analysis of Sustainable Transport.* New York: Routledge.
Geels, F. W., and Schot, J. 2007. Typology of sociotechnical transition pathways. *Research Policy* 36(3): 399-417.
Geels, F. W., and Schot, J. 2010. The dynamics of socio-technical transitions: A socio-technical perspective. In *Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change*, eds. J. Grin, J. Rotmans, J. Schot in collaboration with F. W. Geels, D. Loorbach. New York: Routledge, 11-101.
Genus, A., and Coles A.-M. 2008. Rethinking the multi-level perspective of technological transitions. *Research Policy* 37(9): 1436-1445.
Giddens, A. 1991. *The Consequences of Modernity.* Stanford: Stanford University Press.
Grin, J., Rotmans, J., and Schot, J. 2010. *Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change.* New York: Routledge.
Grübler, A. 2003. *Technology and Global Change.* Cambridge, MA: Cambridge University Press.
Hansen, T., and Coenen, L. 2015. The geography of sustainability transitions: Review, synthesis and reflections of an emergent research field. *Environmental Innovation and Societal Transitions* 17: 92-109.
Hendrix, C. S., and Salehyan, I. 2012. Climate change, rainfall and social conflict in Africa. *Journal of Peace Research* 49(1): 35-50.
Hodson, M., and Marvin, S. 2010. Can cities shape socio-technical transitions and how would we know if they were? *Research Policy* 39(4): 477-485.
Hoffman, P. T. 2015. *Why Did Europe Conquer the World?* Princeton: Princeton University Press.

Hughes, T. P. 1983. *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore, MD: Johns Hopkins University Press.

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.

Jessop, B. 1992. Fordism and Post-Fordism: a Critical Reformulation. In *Pathways to Regionalism and Industrial Development*, eds. A. J. Scott, M. J. Storper. London: Routledge, 43-65.

Kaiser, W. and Schot, J. 2014.*Writing the rules for Europe. Cartels, experts and international Organizations*. Basingstoke, Hampshire: Palgrave Macmillan.

Kanger, L., and Schot, J. 2016. User-made Immobilities: A Transitions Perspective (forthcoming).

Kaplinsky, R. 2011. Schumacher meets Schumpeter: Appropriate technology below the radar. *Research Policy* 40(2): 193-203.

Kingston, C., and Caballero, G. 2009. Comparing theories of institutional change. *Journal of Institutional Economics* 5(2): 151-180.

Köhler, J. 2012. A comparison of the neo-Schumpeterian theory of Kondratiev waves and the multi-level perspective on transitions. *Environmental Innovation and Societal Transitions* 3: 1-15.

Konrad, K., Truffer, B., and Voß, J.-P. 2008. Multi-regime dynamics in the analysis of sectoral transformation potential: evidence from German utility sectors. *Journal of Cleaner Production* 16(11): 1190-1202.

Korotayev, A., and Tsirel, S. 2010. A Spectral Analysis of World GDP Dynamics: Kondratieff Waves, Kuznets Swings, Juglar and Kitchin Cycles in Global Economic Development, and the 2008–2009 Economic Crisis. *Structure and Dynamics* 4(1): 1-55.

Korotayev, A., Zinkina, J., and Bogevolnov, J. 2011. Kondratieff waves in global invention activity (1900-2008). *Technological Forecasting and Social Change* 78(7): 1280-1284.

Kristal, T. 2013. The Capitalist Machine: Computerization, Workers' Power, and the Decline in Labor's Share within U.S. Industries. *American Sociological Review* 78(3): 361-389.

Lachman, D. A. 2013. A survey and review of approaches to study transitions. *Energy Policy* 58: 269-276.

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

Lévi-Strauss, C. 1963. *Structural Anthropology*. New York: Basic Books.

Longhurst, J. *Bike Battles: A History of Sharing the American Road.* Seattle, WA: University of Washington Press.

Manning, P. 2013. *Big Data in History*. Basingstoke, Hampshire: Palgrave Macmillan.

Markard, J., and Truffer, B. 2008. Technological innovation systems and the multi-level perspective: Towards an integrated framework. *Research Policy* 37(4): 596-615.

Mathews, J. A. 2011. Naturalizing capitalism: The next Great Transformation. *Futures* 43(8): 868-879.

Mathews, J. A. 2013. The renewable energies technology surge: A new techno-economic paradigm in the making? *Futures* 46: 10-22.

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

Mathews, J. A., and Tan, H. 2015. *China's Renewable Energy Revolution.* Basingstoke, Hampshire: Palgrave Macmillan.

Mazzucato, M., and Perez, C. 2014. Innovation as Growth Policy: the Challenge for Europe. SPRU Working Paper Series, 2014-13. Available online: https://www.sussex.ac.uk/webteam/gateway/file.php?name=2014-13-swps-mazzucato-perez.pdf&site=25.

Metz, R. 2011. Do Kondratieff waves exist? How time series techniques can help to solve the problem. *Cliometrica* 5(3): 205-238.

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

McDowall, W. 2014. Exploring possible pathways to hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling. *Futures* 63: 1-14.

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

McShane, C. 1994. *Down the Asphalt Path: The Automobile and the American City.* New York: Columbia University Press.

Meadowcroft, J. 2005. Environmental Political Economy, Technological Transitions and the State. *New Political Economy* 10(4): 479-498.

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

Meadows, D. L., Randers, J., and Meadows, D. L. 2004. *Limits to Growth: The 30-Year Update*. White River Junction, VT: Chelsea Green.

Mesoudi, A. 2011. *Cultural Evolution: How Darwinian Theory Can Explain Human Culture and Synthesize the Social Sciences*. Chicago and London: University of Chicago Press.

Mildner, S.-A., Lauster, G., and Wodni, W. 2011. Scarcity and Abundance Revisited: A Literature Review of Natural Resources and Conflict. *International Journal of Conflict and Violence* 5(1): 155-172.

Misa, T. J. 2004. *Leonardo to the Internet: Technology and Culture from the Renaissance to the Present.* Baltimore, MD: Johns Hopkins Press.
Misa, T. J., Brey, P., and Feenberg, A. 2003. *Modernity and Technology.* Cambridge, MA: The MIT Press.
Mokyr, J. 1990. *The Lever of Riches: Technological Creativity and Economic Progress.* Oxford: Oxford University Press.
Mokyr, J. 2012. *The Enlightened Economy: An Economic History of Britain 1700-1850.* New Haven: Yale University Press.
Mom, G. 2004. *The Electric Vehicle: Technology and Expectations in the Automobile Age.* Baltimore, MD: Johns Hopkins University Press.
Moore, J. W. 2015. *Capitalism in the Web of Life: Ecology and the Accumulation of Capital.* London: Verso Books.
Nelson, R. R. 2005. *Technology, Institutions, and Economic Growth.* Cambridge, MA: Harvard University Press.
Nye, D. E. 1998. *Consuming Power: A Social History of American Energies.* Cambridge, MA: The MIT Press.
Østby, G. 2008. Polarization, Inequalities and Violent Civil Conflict. *Journal of Peace Research* 45(2): 143-162.
Papachristos, G., Sofianos, A., and Adamides, E. 2013. System interactions in socio-technical transitions: Extending the multi-level perspective. *Environmental Innovation and Societal Transitions* 7: 53-69.
Penna, C. C. R., and Geels, F. W. 2012. Multi-dimensional struggles in the greening of industry: A dialectic issue lifecycle model and case study. *Technological Forecasting and Social Change* 79(6): 999-1020.
Penna, C.C.R., and Geels, F. W. 2015. Climate change and the slow reorientation of the American car industry (1979-2012): An application and extension of the Dialectic Issue LifeCycle (DILC) model. *Research Policy* 44(5): 1029-1048.
Perez, C. 2002. *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages.* Cheltenham, UK: Edward Elgar.
Perez, C. 2009. The double bubble at the turn of the century: technological roots and structural implications. Cambridge Journal of Economics 33(4):779-805.
Perez, C. 2010. Technological revolutions and techno-economic paradigms. *Cambridge Journal of Economics* 34(1): 185-202.
Perez, C. 2011. Finance and Technical Change: A Long-term View. *African Journal of Science, Technology, Innovation and Development* 3(1): 10-35.
Perez, C. 2013. Unleashing a golden age after the financial collapse: Drawing lessons from history. *Environmental Innovation and Societal Transitions* 6: 9-23.
Piketty, T. 2014. *Capital in the 21st Century*. Cambridge, MA: Belknap Press of Harvard University Press.
Piore, M. J., and Sabel, C. F. 1984. *The Second Industrial Divide: Possibilities for Prosperity.* New York: Basic Books.
Podobnik, B. 1999. Toward a Sustainable Energy Regime: A Long-Wave Interpretation of Global Energy Shifts. *Technological Forecasting and Social Change* 62(3): 155-172.
Raven, R., Schot, J., and Berkhout, F. 2012. Space and scale in socio-technical transitions. *Environmental Innovation and Societal Transitions* 4: 63-78.
Raven, R. P. J. M., and Verbong, G. P. J. 2009. Boundary crossing innovations: Case studies from the energy domain. *Technology in Society* 31(1): 85-93.
Rotolo, D. Hicks, D., and Martin, B. R. 2015. What is an emerging technology? *Research Policy* 44(10): 1827-1843.
Rip, A., and Kemp, R. 1998. Technological change. In *Human Choice and Climate Change*, eds. S. Rayner, E. L. Malone. Columbus, OH: Battelle Press, 327-399.
Sabel, C. F., and Zeitlin, J. 1985. Historical Alternatives to Mass Production: Politics, Markets and Technology in Nineteenth-Century Industrialization. *Past & Present* 108: 133-176.
Schot, J. 2016. Confronting the Second Deep Transition through the Historical Imagination. *Technology and Culture* 57(2), 445-456.
Schot, J., and van Lente, D. 2010. Technology, Industrialization and the Contested Modernization of the Netherlands. In *Technology and the Making of the Netherlands: The Age of Contested Modernization, 1890-1970*, eds. J. Schot, H. Lintsen, A. Rip. Cambridge, MA: The MIT Press, 485-542.
Schot, J., Lintsen, H., and Rip, A. (eds). 2010. *Technology and the Making of the Netherlands: The Age of Contested Modernization, 1890-1970.* Cambridge, MA: The MIT Press.
Schot, J., and Rip, A. 2010. Inventing the Power of Modernization. In *Technology and the Making of the Netherlands: The Age of Contested Modernization, 1890-1970*, eds. J. Schot, H. Lintsen, A. Rip. Cambridge, MA: The MIT Press, 13-46.
Scranton, P. 1997. *Endless Novelty: Specialty Production and American Industrialization, 1865-1925.* Princeton: Princeton University Press.
Stiglitz, J. E. 2012. *The Price of Inequality.* London: Allen Lane.
Steffen, W. et al. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223): 736-746.
Smith, A., and Stirling, A. 2007. Moving Outside or Inside? Objectification and Reflexivity in the Governance of Socio-Technical Systems. *Journal of Environmental Policy & Planning* 9(3-4): 351-373.
Smith, A., Stirling, A., and Berkhout, F. 2005. The governance of sustainable socio-technical transitions. *Research Policy* 34(10): 1491-1510.

Steffen, W. et al. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223): 736-746.
Stirling, A. 2008. “Opening up” and “closing down” power, participation, and pluralism in the social appraisal technology. *Science, Technology, and Human Values* 33(2): 262-294.
Stirling, A. 2009. Direction, Distribution, Diversity! Pluralising Progress in Innovation, Sustainability and Development.SPEPS Working Paper 32, STEPS Centre, University of Sussex.
Truffer, B., Murphy, J. T., and Raven, R. 2015. The geography of sustainability transitions: Contours of an emerging theme. *Environmental Innovation and Societal Transitions* 17: 63-72.
Turner, G. M. 2008. A comparison of *The Limits to Growth* with 30 years of reality. *Global Environmental Change* 18(3): 397-411.
Tylecote, A. 1992. *The Long Wave in the World Economy: The Present Crisis in Historical Perspective.* London: Routledge & Kegan Paul.
United Nations, Department of Economic and Social Affairs. 2015. *World Population Prospects: The 2015 Revision.* Available online: http://esa.un.org/unpd/wpp/publications/files/key_findings_wpp_2015.pdf.
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.
Valverde, S., and Solé, R. V. 2015. Punctuated equilibrium in the large-scale evolution of programming languages. *Journal of the Royal Society Interface* 12: 20150249.
Van Driel, H., and Schot, J. 2005. Radical innovation as a multilevel process: introducing floating grain elevators in the Port of Rotterdam. *Technology and Culture* 46(1): 51-76.
Verbong, G, and Geels, F. 2007. The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960-2004). *Energy Policy* 35(2): 1025-1037.
Vries, P. 2013. *Escaping Poverty: The Origins of Modern Economic Growth.* Vienna: Vienna University Press.
Wallerstein, I. 1974-2011. *The Modern World System*, 4 volumes. New York: Academy Press; Berkeley: University of California Press.
Wells, P., and Nieuwenhuis, P. 2012. Transition failure: Understanding continuity in the automotive industry. *Technological Forecasting & Social Change* 79(9): 1681-1692.
Whitehead, A. N. 1925. *Science and the Modern World.* New York: Macmillan Company.
WGBU (German Advisory Council on Global Change) 2011. *World in Transition: A Social Contract for Sustainability*. Available online: http://www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2011/wbgu_jg2011_kurz_en.pdf.
World Bank. 2012. *Inclusive Green Growth: The Pathway to Sustainable Development.* Available online: https://issuu.com/world.bank.publications/docs/9780821395516.

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