UNIVERSITY OF OXFORD
Institute for
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Transformational Change: Parallels for addressing climate and development goals

Penny Mealy & Cameron Hepburn
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1 Introduction

Climate change and poverty alleviation are, as Stern (2016) has coined, 'the twin defining challenges of our century'. Historically, efforts to address these two challenges have been conflicted. Adverse impacts of climate change are likely to hit the poorest of this world hardest, but traditional industrial routes out of poverty are dangerously emissions-intensive. Such tensions have been major sticking points in earlier climate negotiations and largely underpinned the failure of the 2009 Copenhagen COP to reach a global climate agreement (Nordhaus, 2010).

However, two important developments suggest a new global readiness to move beyond historical conflicts and instead take advantage of key commonalities and collective interests. The 2015 adoption of the Sustainable Development Goals (SDGs) demonstrated an acute awareness that any plan to advance living standards of present and future generations must address the inseparable links between people, the planet and prosperity (UN, 2015; Griggs et al., 2013; Brown, 2015). Further, the Paris Agreement (UNFCCC, 2015), which has been ratified by an overwhelming majority of countries, provides a promising new international platform to progress a unique collective framework for global climate cooperation. The confluence of these global agendas represent an historic opportunity to marry efforts on climate and development fronts and drive significant progress on sustainable development.

Against this encouraging backdrop, this chapter draws attention to a somewhat under-appreciated, but profoundly important commonality in the twin climate and development challenges: both require societies to navigate and manage system-wide transformative change.

Unfortunately, transformational change is a concept that is not yet well defined or understood. To our knowledge, a generally accepted definition of transformational change does not as yet exist (Mersmann et al., 2014). There is also limited consensus on how it should be meaningfully measured – particularly as transformational change often involves dynamic processes occurring at multiple scales and dimensions (Geels et al., 2016; Turnheim et al., 2015). Further, while traditional economic modeling frameworks are well-suited for studying marginal changes over short-term horizons, they are poor tools for analysing dis-equilibrium dynamics, non-linear feedbacks and emergent properties that commonly characterise transformational change processes. As a better understanding of the process of transformational change could catalyse progress on both climate and development fronts, this chapter explores parallel efforts in respective fields.

First, we examine the nature and importance of transformational change processes in climate and development contexts. Unprecedented changes in both the low carbon landscape and global economic environment have taken many by surprise. While these unfolding dynamics are invalidating traditional analytical approaches based on assumed patterns of incremental change and challenging long-held notions about growth and development, they are also offering much needed alternative possibilities for achieving climate and development goals. Indeed, given the sheer magnitude of climate and development challenges – and the rate at which change must occur to mitigate the worst climate impacts, being able to both navigate and *drive* the process of transformational change is now seen as a critical policy imperative.

Although significant efforts are underway to understand transformative change processes in respective climate and development fields, we argue that there are also key advantages from better integration across domains. For example, by considering the dynamics of economic development processes, climate policy can better account for mitigation opportunities, particularly as countries shift from energy intensive manufacturing activities towards services. Similarly, by taking advantage of the present impetus towards low-carbon futures, developing countries could seize an unprecedented opportunity to not only accelerate their growth, but also attain a much higher *quality* of sustainable, inclusive and resilient development.

Second, we explore empirical patterns of transformational change in climate and development contexts. We find that climate and development fields share a number of things in common. Aggregate changes (e.g. in GDP/capita or emissions) are often broken down into between-sector and within-sector changes, and key driving forces of change invariably relate to technology, preferences and their endogenous evolution. While historical stylized facts associated with the development process (such as the shift from agriculture to manufacturing to services) have been well documented, empirical patterns associated with low-carbon transformations are still emerging, and also likely to vary more across countries with different productive structures.

Third, we compare and contrast four alternative methodological tools for analysing and modeling transformational change: network analysis, computable general equilibrium (CGE) models, macro-econometric/input-output models, and agent based models. Each has key strengths and weaknesses, which are important to bear in mind when applying them to policy questions relating to transformational change. Moreover, as models influence behavior in the real world, getting these right, or at least less wrong, is not a mere academic curiosum but could be vital for making simultaneous progress on climate and development goals.

This chapter proceeds as follows: In section 2 we examine the importance of transformational change in climate and development contexts and highlight key areas where more amalgamation across domains could be advantageous. Section 3 examines existing approaches to measure transformational change and identifies commonalities across climate and development frameworks. Section 4 reviews existing modeling methodologies and reflects on their ability to appropriately model transformational change. Section 5 concludes.

2 Transformational change in climate and development contexts

2.1 The importance of transformational change in achieving climate and development goals

The past decades have seen unprecedented transformations across both economic and low carbon fronts. Rapid technological progress, population growth, urbanisation and changing global market structures are combining to shape many countries' development trajectories in new and interesting ways (Fankhauser and McDermott, 2016). Equivalently, startling reductions in renewable energy costs and mounting international cooperation to curb emissions are drastically changing the contours of the low carbon landscape (Trancik, 2014). Such changes have prompted a rethink of long-held notions about growth and development. They also invalidate commonly used traditional analytical approaches based on assumed patterns of incremental change. However, given the scale of climate and development challenges – and the pace at which change needs to occur to mitigate the worst climate impacts, navigating and *driving* the process of transformative change is now seen as an urgent policy imperative.

Indeed, many scholars are now stressing that without radical, non-marginal change limiting global warming to 2'C will be extremely difficult (Reid et al., 2010; Burch et al., 2014; Fankhauser and Stern, 2016). The magnitude of emissions reductions required in the rapidly diminishing time frame necessitates much more than incremental change along existing developmental and technological paradigms (Perez, 2015; Zenghelis, 2015). At the same time, developing countries are encountering a significant paradigm shift of their own. With traditional industrial development routes now potentially less viable due to impinging automation and globalization forces (Rodrik, 2016), development agencies and policy makers are facing the prospects of paving profoundly different pathways to prosperity in the 21st century.

While significant research efforts are underway to understand transformative change processes in respective climate and development fields, there are also key advantages from better integration across domains. In what follows, we outline key areas where climate policy could benefit from better accounting for economic transformation processes and equally, where development policy could benefit from the present impetus to transition towards low-carbon futures.

2.2 Why climate mitigation efforts should better account for economic transformation processes

The Paris Agreement (UNFCCC, 2015) represented a significant step forward in achieving universal consensus and commitment to move towards a sustainable future. However, there is still a significant gap between country Nationally Determined Contributions (NDCs) and the emissions reductions required by 2030 to plausibly remain on a 2'C pathway (Rogelj et al., 2016). In order to attain a reasonable chance of avoiding a rise in global average temperatures by more than 2'C, policy makers will need to harness as many emission reduction opportunities as possible. Better accounting for non-linear dynamics associated with low-carbon technology learning curves, uptake rates and shifts in consumer behavior and societal norms is a critical first step, and improved understanding of what drives these tipping points could help us speed them up (Russill and Nyssa, 2009; Aghion et al., 2014; Boyd et al., 2015).

However, understanding emissions implications of future economic structural shifts is also key. One of the biggest drivers of errors in historical energy and emissions projections is the failure to anticipate macroeconomic changes – particularly as a country shifts from energy intensive manufacturing activities towards services

(Grubb et al., 2015). Most climate-economy models take the structure of the economy as fixed and rarely incorporate macroeconomic dynamics (Zenghelis, 2015). This is particularly problematic for countries like China, whose future emissions trajectory will have important climate consequences, but is also undergoing a process of rapid socio-economic transformation (Green and Stern, 2017). For example, Grubb et al. (2015) recently reviewed projections of 89 scenarios from 12 different models for China's emissions through to 2030. They found that not only is the range of projections extremely large indicating a high degree of uncertainty, most scenarios do not account for the economy's macroeconomic structure and the potential to shift away from its currently high share of manufacturing. Given the consistent historical trend for countries to transition towards less energy-intensive service based activities as incomes rise, incorporating structural change dynamics in climate-economy models could depict very different climate implications of China's future development path.

While this chapter is primarily focused on drawing parallels between economic transformation and the low carbon transformation, it is worth noting that climate adaptation efforts can also benefit from a better understanding of the economic transformation process. Measures to lessen adverse climate change impacts have traditionally been approached as a static concept, with efforts to reduce vulnerability in developing countries often focusing on protecting existing structures and livelihoods, such as safeguarding agricultural output. However, as many developing countries are undergoing a process of socio-economic transformation, overly static adaptation plans could hamper development progress by placing too much emphasis on sectors that are likely to become less important over time (Bowen et al., 2016; Kocornik-Mina and Fankhauser, 2015). In light of the important links between climate risks and the development process, there has recently been increased interest in understanding what might constitute 'climate-resilient development' (Denton et al., 2014). This approach seeks to better account for the dynamism of the development process and calls for adaptation efforts to become more transformational (Fankhauser and McDermott, 2016).

2.3 Why development should better account for low-carbon transformation processes

When it comes to the key development objective of lifting people out of poverty, climate change has traditionally been seen as a key stumbling block, with the world's poorest and most vulnerable likely to shoulder the biggest burden of climate impacts (Collier et al., 2008; Brown, 2015; Hallegatte et al., 2015; Althor et al., 2016). Further, well-worn emissions-intensive industrial pathways that led today's advanced economies to prosperity are now recognized as being incompatible with the rapidly diminishing global carbon budget (IPCC, 2007; Stern, 2008). Consequently, the ability of developing countries to 'catch-up' to advanced countries' income levels by following well established manufacturing routes (Rodrik, 2012) might now be less feasible. This leaves many developing countries with the challenging prospect of scouting out new, un-trodden and uncertain paths to prosperity.

However, with new momentum building in the low carbon space, particularly on the technological and international negotiation fronts, climate change may now present developing countries with an unprecedented opportunity for growth acceleration (ECA, 2016). Never in history have developing countries been able to leverage such compelling global pressure and financial assistance to adopt new technologies, develop better infrastructure and protect natural capital. Further, as development agencies and policy makers are now increasingly calling for new modes of sustainable, inclusive and resilient development, the 21st century could see developing countries attaining a much higher quality of development than their predecessors (Garnaut et al., 2013; Mlachila et al., 2014; UNIDO, 2016).

A particularly important case in point relates infrastructure development. The current stock of infrastructure presently accounts for 60 per cent of global greenhouse gas emissions and if existing, long-lived energy and transportation assets are not stranded, they are projected to commit the world to a significant degree of warming (Davis et al., 2010; Guivarch and Hallegatte, 2011; Pfeiffer et al., 2016) However, with the number of people living in cities projected to increase from 3.5 billion to 6.5 billion by 2050 (Fankhauser and Stern, 2016) and the overwhelming majority of this increase likely to occur in Africa and Asia (UN, 2014), developing countries have a one time opportunity to shape more clean, compact and coordinated cities and urban structures (Floater et al., 2014; NCE, 2016). Getting infrastructure right has an enormous potential to curb emissions and lock rapidly developing countries in to a low-carbon growth trajectory (Bhattacharya et al., 2015). Further, as noted by Fuller and Romer (2014),"nothing else will create as many opportunities for social and economic progress".

3 Empirical patterns of transformational change in climate and development contexts

Despite its widely recognized importance in achieving climate and development goals, transformational change is a concept that is not yet well defined or understood. Like notions of ‘world peace’ and ‘living happily ever after’, transformational change often inspires broad endorsement and significant approval, but is challenging to definitively pin down. To our knowledge a generally accepted definition does not as yet exist. Nevertheless, development and climate economists have examined empirical patterns of system-wide transformational change within their respective fields. Although there are distinct differences, we highlight important commonalities that could stimulate shared learning.

3.1 Empirical patterns of structural change in the development process

When examining system-wide transformative change in the context of development, economists often distinguish between changes arising from two key processes. The first relates to the structural shifts between sectors, which usually occurs as resources are allocated from low productivity to higher productivity activities. The second relates to changes occurring within sectors, which are often related to economy-wide productivity increases due to improvements in key economic ‘fundamentals’, such as institutions or human capital (Rodrik, 2013).

In examining structural shifts, economists have found that over the last 200 years, economic growth and development has generally been associated with successive transitions across three broad sectors. Early in a country’s development phase, most people and resources are engaged in subsistence agriculture, where labour productivity is very low (Herrendorf et al., 2014). However, as productivity improves, agricultural workers are released to engage in higher value-add industrial activities. Employment and value added shares in manufacturing rise begin rising as agriculture shares decline. As the economy advances further, the manufacturing share reaches a peak and begins declining, as the service sector becomes much more dominant. These empirical trends are illustrated in Figure 1, where Herrendorf et al. (2014) have plotted the empirical decline in agriculture, inverted U-shape in manufacturing and rise in services experienced by ten advanced countries.

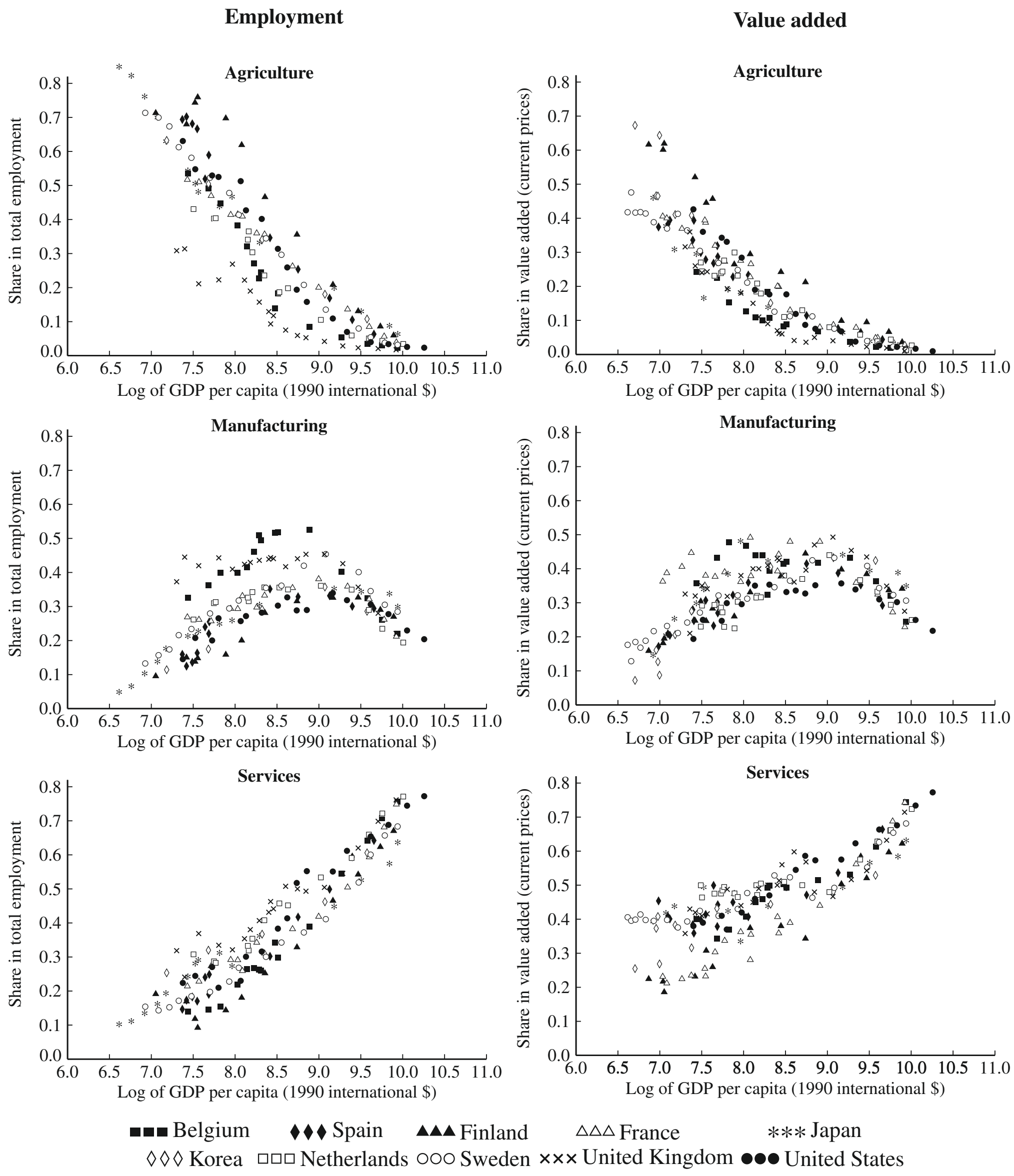

Figure 1: Sectoral shares of employment and added for selected developed countries: 1800-2000. Figure reproduced with the permission of Herrendorf et al. (2014).

To understand what drives the observed structural changes, researchers have focused on two key factors. The first relates to technological progress. As agricultural workers adopt new technologies and techniques, the increase in agricultural productivity allows surplus labour to then be released to other industrial or services activities that pay higher wages (Lewis, 1954). Further, since rates of technological change differ across sectors, some sectors will generate higher improvements in growth and living standards than others (Chenery, 1986). The second factor relates to how consumer preferences change with rising income. As people become richer, they tend to spend a lower relative share of their income on food and more on durable (manufacturing) goods and services (Chenery, 1979; Cypher and Dietz, 2008). This increases domestic demand for new non-agricultural industries and economic activity.

3.2 Empirical patterns in the transition towards a low carbon economy

When examining shifts towards a low carbon economy, researchers have also examined empirical patterns in how countries' emissions change as the economy evolves. A sizable body of empirical research has examined the 'Environmental Kuznets Curve' (EKC) hypothesis, which postulates an inverted U shape relationship between pollutants and per capita income (Cole et al., 1997; Stern et al., 1996). One explanation for this posited relationship relates to the evolution of economic structure – as a nation progresses from relatively clean agricultural activities to dirty industrial manufacturing activities to cleaner service-based activities, one would expect emissions to rise and subsequently fall. A second explanation relates to the evolution of preferences – as societies become richer, the general expectation is that they are more likely to have a greater preference for environmental quality (Dinda, 2004). Empirical evidence strongly supports the upward sloping part of the EKC, with many countries tending to experience an increase in emissions in the early phases of their development. However, there has been relatively inconclusive evidence to support the EKC's downward sloping section (Kaika and Zervas, 2013). A number of studies have found that urban or local air quality indicators that directly impact human health follow the hypothesized U relationship with income (Grossman and Helpman, 1993; Selden and Song, 1994; Stern and Common, 2001). For other pollutants, the trend observed among higher income countries tends to be quite mixed, with emissions tending to depend more on country-specific conditions, technologies and policies than its prosperity (Ota, 2017; Fankhauser and Jotzo, 2018).

The Kaya identify offers a different lens to view system-wide changes in countries' emissions (Raupach et al., 2007; Rosa and Dietz, 2012). This identity is specified as follows

$$C \equiv \frac{C}{E} \cdot \frac{E}{Y} \cdot Y \tag{1}$$

where C relates to emissions from human sources, E relates to energy consumption, and Y relates to economic output.

This formulation allows progress towards the low carbon economy to be analysed in terms of reductions in carbon intensity of energy $(\frac{C}{E})$, or reductions in the energy intensity of economic output $(\frac{E}{Y})$, or both. Fankhauser and Jotzo (2018) recently illustrated how countries' carbon intensity and energy intensity have evolved over time. As shown in Figure 2, energy intensity has been steadily decreasing in all countries over the 1990-2011 period. However, only high-income countries are managing to decarbonize their energy.

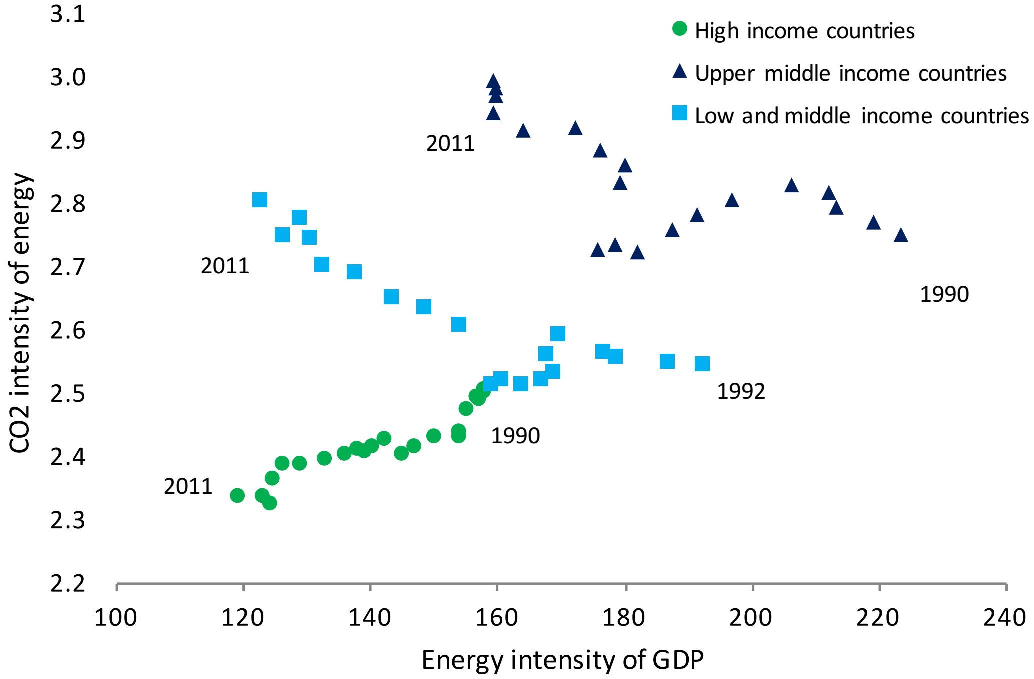

Figure 2: Long term trajectory of countries' carbon intensity of energy and energy intensity of GDP. Figure reproduced with the permission of Fankhauser and Jotzo (2018).

In a similar fashion to the study of empirical patterns in development economics, aggregate changes in carbon intensity and emissions intensity are also often broken down into structural shifts and system-wide efficiency improvements (Lenzen, 2016). However, unlike the relatively consistent structural dynamics and drivers observed in the economic development process, patterns in emissions and energy consumption across countries and sectors are more mixed. This in part is due to studies employing a range of different decomposition methodologies, industrial sector classifications and applying analysis to a wide diversity of regions and time periods (Su and Ang, 2012). But it is also likely that factors driving emissions are different for different economies (Yao et al., 2015).

3.3 Key commonalities

In our brief overview of empirical frameworks commonly applied to understand patterns of change in development and emissions-related areas, three commonalities are apparent. First, both fields seek to understand observed dynamics in similar ways. Across the development and emissions-related literature, 'transformative change' is recognized as a phenomenon involving between sector changes and within sector changes. Key aggregates of interest are consequently decomposed into variation arising from sectoral shifts and system-wide efficiency improvements.

Second, both domains have significant commonalities in their key objective. While development economists are generally interested in what drives increases in GDP and climate economists are concerned with what reduces emissions, both tend to view system-wide progress through the lens of a productivity measure – for development, improving labour productivity is what matters, while for climate change, improving carbon productivity is key. However, it is this commonality that drives significant conflict. Traditionally, economies have increased their labour productivity by increasing their use of energy. Due to the emissions intensity of traditional energy sources, this in turn has generated greater emissions (Taylor, 2009).

The extent to which these twin objectives can be pursued together ultimately depends on our ability to decouple emissions from the development process (Hepburn and Bowen, 2013). As shown in Figure 2, many advanced economies are moving in the right direction, particularly as increasing value add is derived from digitally enhanced material-light, intelligence-heavy activities (Baptist and Hepburn, 2012). However, current rates of progress are presently not sufficient to plausibly keep the planet on a 2'C pathway (NCE, 2014). A further critical sticking point remains for developing countries. As no advanced economy has ever become rich without undergoing an emissions-intensive industrial phase (Felipe et al., 2017), it is presently unknown whether development on the basis of 'industries without smoke stacks' is feasible (Page, 2015).

Such challenges underscore the pressing need to understand and leverage drivers of transformational change towards low-carbon development pathways. Incremental change along existing paradigms will clearly fall short (Perez, 2015). This brings us to the third commonality across climate and development research domains: in both economic and low carbon transformation studies, key driving forces of change generally relate to either technological improvements (which alter labour or carbon productivity rates) or demand-side factors relating to consumer preferences.

In relation to technological change, a key focus in the climate literature has been to better understand the non-linear dynamics associated with cost improvements in renewable energy technologies (Koh and Magee, 2008; Schilling and Esmundo, 2009). Research has also investigated the potential for policy to influence the pace of change through stimulating greater production and making directed investments in R&D (Menanteau et al., 2003; Fischer and Newell, 2008; Farmer and Lafond, 2016). The nature of knowledge spillovers is a further important factor, with research showing that low-carbon innovation tends to have greater positive benefits for the local economy than innovation incumbent, carbon-intensive technologies (Dechezleprêtre et al., 2014a,b). Many studies have also examined the significant potential for developing countries to take advantage of new decentralized forms of energy distribution platforms, (such as mini-grids) and leap-frog the traditional centralized energy distribution systems that characterise most developed countries (Alstone et al., 2015; Levin and Thomas, 2016).

However, technological diffusion is also a critical facilitating (and limiting) factor in both development and low carbon transitions. In development research, the difficulty transferring productive knowledge from advanced countries to less developed countries is a common explanation for why some countries remain poor (Keller, 2004; Hidalgo et al., 2007; Hausmann et al., 2014; Bahar et al., 2014). Understanding the likelihood of successful technological transfer and its underpinning drivers is profoundly relevant for both development and climate policy makers seeking to facilitate transformative change. There are a number of important and encouraging developments in this field, which we will return to in the following section.

The nature of demand-side influences, particularly as they relate to underlying consumer preferences has received substantially less research attention in both climate and development fronts. In an extensive review of over 900 articles on structural change, Silva and Teixeira (2008) noted that only a small minority of articles examined demand-side factors. While there is a growing body of research relating to behavioural aspects of energy consumption and climate change awareness (Gowdy, 2008; Steg, 2008; Dietz et al., 2009; Gillingham et al., 2009) surprisingly little research seeks to address climate implications of how preferences may evolve over extensive time periods. The long time scales that development and climate policy are often concerned with tends to invalidate standard approaches that take preferences as given and assume future preferences will look like the past. Further, as Mattauch and Hepburn (2016) argue, failing to account for preference evolution and the extent to which preferences can be shaped by policy can significantly overestimate the cost of climate mitigation. The same is also likely to be true for many cost-benefit analyses applied in development contexts, such as large-scale infrastructure investments. The nature of preference formation and its co-evolution with policy choices is an important area for future research that will likely have important implications for understanding transformative change in both development and climate change related areas.

4 Methodological tools for modeling and understanding transformational change in climate and development contexts

A wide range of analytical frameworks and decision-making tools are employed within development and climate domains. This section focuses on four key approaches and considers their relative strengths and weaknesses for helping researchers and policy makers better understand and manage the process of transformational change.

4.1 Network analysis

Network analysis, which has become a widely embraced analytical framework within a diverse range of disciplines, offers important avenues for understanding transformational change. While traditional methods have tended to study transformational change in terms of sectoral shifts in resource allocation and within-sector productivity improvements, network analysis allows analysis of the connections *across sectors* and provides a means of estimating the probability of transitioning from one sector to another.

Hidalgo et al. (2007)'s application of network analysis to global trade data is one of the most notable contributions to the development context. Their 'Product Space' network, where traded products are represented as nodes linked to each other if they are more likely to require similar production capabilities (or know-how), has received significant attention from both scholars and policy makers as it provides a new lens to both visualize countries' productive structures and analyse feasible development pathways. Hidalgo et al. (2007) work is based on a theory advanced in the economic complexity and economic geography literature, which proposes that economic development is path dependent due to the underlying knowledge accumulation process. Just as it is easier to become good at making shirts if you already now how to make trousers, Hidalgo et al. (2007) used network analysis to demonstrate that it is easier for countries to become competitive in new products that require similar capabilities (or production know-how) to what they already know how to do.

This style of analysis has also been applied to regional and industry data (O'Clery et al., 2016; Neffke et al., 2011; Boschma et al., 2013), labour-flows data (Neffke and Henning, 2013; Neffke et al., 2017) and input-output data (Radebach et al., 2016), and offers a number of important insights for developmentally oriented transformational change. First, not all product specialisations (and productive capabilities) are equal in terms of their knowledge spillover benefits and future diversification opportunities. The Product Space has a distinct core-periphery structure with manufacturing products (such as metals, machinery and chemicals) occupying the densely connected core of the network, and other products (such as agriculture and mining) tending to locate in the sparsely connected periphery. This finding further re-iterates the importance of manufacturing in the developmental process. Not only is manufacturing associated with unconditional convergence in labour productivity (Rodrik, 2012), which means that industries starting at lower labour productivity levels experience more rapid labour productivity growth. Manufacturing sectors also tend to have higher connectivity (in terms of shared capabilities and knowledge spillover opportunities) with other industries. As such, manufacturing has a unique ability to expand the set of 'adjacent possible' industries that are relatively easy to diversify into (Hausmann et al., 2015).

Second, the position of countries' exports in the Product Space can help identify specific new development opportunities that countries could more easily transition towards. Hidalgo et al. (2007) showed that countries were much more likely to diversify into products that were 'nearby' to their existing exports in the Product Space. By developing a measure (known as 'proximity density') that captures how similar a country's current exports are to a given undeveloped product in terms of their requisite production capabilities, they showed that while the probability of moving to exports that were far away (proximity density = 0.1) was almost zero, the probability of transitioning increases to 0.15 if a country's export basket contains closer products (proximity density = 0.8). The proximity density measure is particularly useful for industry players or policy makers seeking to identify 'adjacent possible' development opportunities that are more likely to be successful. However, when it comes to driving radical transformations in countries' productive structures, one of the key challenges is that it invariably involves big, difficult jumps in knowledge accumulation across the Product Space.

Recently, work has also sought to apply this type of analysis to examine transitions towards the green economy. By applying network analysis to a dataset of traded environmental products, Mealy and Teytelboym (2017) examined countries' green productive capabilities and their capacity to develop new green industries in the future. They showed that network-based measures, such as their Green Complexity Potential measure, were significantly predictive of future increases in countries' green trade competitiveness. Moreover, by exploring countries' positions in the 'green product space' and investigating how countries' competitiveness in green products evolved over time, Mealy and Teytelboym (2017) found that green diversification is strongly path-dependent: countries gaining early success in green capabilities tend to have much greater opportunities for diversifying into new product markets.

While recent efforts to incorporate network analysis into development and climate related research is yielding promising results, considerable future work awaits – particularly in better understanding the dynamic nature of networks. Although existing efforts have illuminated cross-country differences in productive structures, we are yet to understand how and why they change in particular ways. Further, very little research has examined the extent to which a nation's productive structure may be shaped by policy.

4.2 CGE models

The overarching paradigm currently used to conduct policy analyses in both fields is computable general equilibrium (CGE) modeling. CGE models are large-scale numerical models that aim to simulate how the economy might evolve in response to changes in policy, technology or other exogenous events (such as a drought or flood). Often described as an exercise of 'theory with numbers' (Wing and Balistreri, 2014) they encompass two key components: (i) detailed data on the structure of the economy and (ii) a theoretically derived system of equations dictating how the economy is likely to respond to particular changes. The underlying data used to calibrate CGE models are based on input-output tables or social accounting matrices. Aiming to provide a 'snapshot' of the economy at a particular point in time, these datasets include transaction values between key economic sectors (including government and representative households) and econometrically estimated parameters (or elasticities) capturing how different economic actors respond to changes in relative prices. The data are linked to a system of equations based on general equilibrium theory. These equations are numerically solved to determine how the simulated economy transitions to a new equilibrium by rebalancing supply and demand in different markets (Wing, 2004).

The ability of CGE models to incorporate data on the current state of the economy and provide theoretically grounded projections of its future evolution has made them popular tools within development and climate policy analysis. In development policy, CGE models have been frequently applied to examine the impacts of trade liberalization migration, industrial policy and pro-poor growth strategies (Ackerman and Gallagher, 2008; Devarajan and Robinson, 2013). In climate policy, CGE models are commonly applied to examine the cost and benefits associated with the introduction of a carbon tax, emission-trading schemes and subsidy-based schemes such as feed-in tariffs (Wing, 2009; Adams and Parmenter, 2013). They form the core component of some Integrated Assessment Models (Bosetti et al., 2006; Scrieciu et al., 2013; Hasegawa et al., 2017), which are frequently used by policy makers to understand inter-relationships between economic, energy and climate systems (Farmer et al., 2015).

When applied to reasonably short-term horizons, CGE models have key strengths. Their capacity to explicitly capture interrelationships between markets for final goods, intermediate goods, government expenditure and households enable policy analysts to quantitatively study how the impacts of a particular change may filter through the economy and directly or indirectly impact different sectors and households (Wing, 2004). Unlike input-output models (discussed below), which are limited in their ability to incorporate actors' behavioral responses to prices and consequently tended to overestimate impacts associated with a given change, CGE models assign a more important role to prices and supply-side constraints (West, 1995). By explicitly specifying household utility functions, CGE models are also able to provide an estimate of the aggregate income and welfare impacts associated with a particular change. The ability to provide a quantitative estimate for impacts on 'winners' and 'losers' of proposed policies have made CGE models significantly influential in many policy debates (Devarajan and Robinson, 2002; Hughes et al., 2016).

However, when CGE models are applied to longer time horizons, or to the context of transformational change, CGE models encounter a number of issues. First, many CGE models have encompass a relatively static framework, meaning that the modeled producers and consumers make optimizing decisions in a single period (Ahmed and O'Donoghue, 2007). In these models, policy analysis is based on a comparison of two alternative future equilibrium states of the economy – one with the policy change and one without. As these models do not explicitly represent the process of adjustment from one equilibrium to another, any economic impacts associated with transitional dynamics are unable to be accounted for (Scrieciu, 2007; Ackerman and Gallagher, 2008).

An alternative class of *dynamic* CGE models aims to better trace model variables over the projected time path – usually at yearly intervals. These models can be divided into two types: recursive dynamic models and forward looking models (Devarajan and Robinson, 2013). Unfortunately, neither of these options provide convincing frameworks for realistically capturing agent behaviours or structural dynamics associated with transformational change. Recursive dynamic CGE models assume that agents are completely myopic and make optimizing decisions only on the basis of current and past prices and other model variables. Agents' lack of consideration about the future prevents meaningful analysis of any inter-temporal investment and savings decisions (Babiker et al., 2009).

In contrast, forward-looking models do encompass agents that incorporate the future expectations into their decisions (Pratt et al., 2013). However, these models are usually characterized by agents who are unrealistically perfectly rational and omnisciently able to solve inter-temporal optimization problems over all modelled periods (Babiker et al., 2009; Richiardi, 2015). While dynamic stochastic general equilibrium (DSGE) models enable agents to explicitly incorporate uncertainty about future states of the world, these models are usually so computationally intensive that much of the important economic sectoral detail (which makes these models useful in the first place) needs to be significantly simplified (Devarajan and Robinson, 2013). In addition, projections produced by most forward-looking models are, by construction, smooth, efficient adjustments along a balanced equilibrium path, which are hardly appropriate to characterise the turbulent, out-of equilibrium dynamics often associated with societies experiencing transformational change (Nordhaus and Tobin, 1972; Rezai et al., 2013).

A second issue complicating the application of CGE models to transformational change is their heavy reliance on equilibrium outcomes to characterize dynamics and future projections. Almost all CGE models assume capital and labour markets clear – usually instantaneously at each modeled time period. Not only is this at odds with historical observations in which economic activity was commonly subject to long, unanticipated recessions, persistent unemployment (Blanchard and Summers, 1987), 'secular stagnations' (Hansen, 1939) and institutional-induced capital (Harberger, 1959), it also misses essential characteristics of the development and low-carbon transition process that are important for policy makers to account for (DeCanio, 2003; Lane-Visser, 2015). For example, Chenery (1979) emphasizes that as developing economies are often characterized by the persistence of surplus labour and under-utilized capital, models should be designed to allow for the existence of disequilibrium rather than exclude it by assumption. Similarly, a number of scholars have argued that assuming a first-best world where all resources are optimally employed negates the potential economic benefits that green stimulus industrial policies could potentially provide to stagnant or depressed economies

(Barker et al., 2012; Hasselmann and Kovalevsky, 2013; Wolf et al., 2013). While recent developments in new Keynesian style DSGE models have incorporated frictions in price and wage adjustments and even the possibility of involuntary unemployment (Kemfert, 2003; Smets and Wouters, 2007; Christiano et al., 2010) , few have been applied to climate or development policy (Scrieciu et al., 2014; Fagiolo and Roventini, 2016).

4.3 Macro-econometric and input-output simulation models

Macro-econometric and input-output simulation models offer an alternative modeling framework that involves less restrictive assumptions about optimization and equilibrium. These are similar to CGE models in that they are based on detailed economic sectoral data (such as input-output or social accounting matrices) and are able to capture production and consumption flows across different industries. Their dynamics are also built on a system of equations. However, unlike CGE models, they are less strictly tied to neoclassical general equilibrium theory.

Macro-econometric and input-output simulation models instead draw on a more diverse range of economic fields (such as behavioral, ecological and evolutionary economics (Scrieciu et al., 2013)) and alternative economic paradigms (such as the Keynesian or neo-Keynesian framework, where demand is the key driving force of growth and supply adjusts to meet demand, subject to supply constraints (Boulanger and Bréchet, 2005; Rezai et al., 2013)). Instead of making optimization assumptions, they draw on historical data and econometrics to characterise key behavioural parameters and are said to implicitly characterise a form of bounded rationality (Barker et al., 2012). Macro-econometric simulation models also differ to CGE models in their price formation. Rather than determining prices by imposing market-clearing assumptions, they employ a markup on unit costs, which depend on the level of competition in each sector (Cambridge Econometrics, 2014).

Macro-econometric and input-output simulation models are generally estimated using reasonably long stretches of time-series data and have the advantage that they can account for out-of-equilibrium dynamics that may have characterized historical observations. An important implication is that, unlike CGE models, they can capture the existence of unemployment and underutilized resources, which are particularly relevant considerations when assessing the *benefits* of industrial policies or green stimulus measures (Barker et al., 2016; IRENA, 2016). These types of models are also well suited to capture technological detail underpinning different sectors, as well as direct and indirect effects of endogeneous technological change (Lutz et al., 2007; Wiebe and Lutz, 2016).

On the one hand, macroeconometric models are less bounded by the 'straight-jacket' of strong general equilibrium theoretical impositions. However, on the other hand, they have to be much more intimately tied to historical data. This heavy reliance on past data to estimate future projections can be particularly problematic in the context of transformational change, as by definition, such a process entails a future state that could look significantly different from historical trends (Köhler et al., 2006; Scrieciu, 2007). Moreover, the fairly rigid format of input-output tables makes it challenging to consider how the industrial structure of an economy may evolve in response to climate or development policies.

4.4 Agent-based (multi-agent) models

Agent-based (or multi-agent) models offer yet another modeling paradigm. They aim to simulate the behavior of social or economic systems by explicitly representing heterogeneous, networked agents that interact and make decisions through prescribed behavioural rules (Bonabeau, 2002; Farmer and Foley, 2009). Agents do not need to necessarily make optimizing decisions, but can be programmed to make decisions in accordance with a number of behavioural typologies that are usually informed by empirical studies (Valbuena et al., 2008; Smajgl et al., 2011). A key advantage of this modeling paradigm, which is not accessible in CGE or macroeconometric simulation models, is its ability to explicitly model how macro-level dynamics arise from the (often probabilistic) interaction of these heterogeneous entities (Holland and Miller, 1991; Vespignani, 2012; Mercure et al., 2016). This emergence attribute is commonly examined in studies investigating social and collective phenomena, such as traffic jams and stock market crashes (Farmer and Foley, 2009). However, it is also known to be an important characteristic underpinning the 'tipping-point' dynamics associated with technological adoption and product diffusion rates (Dosi, 1982; Silverberg et al., 1988), social opinions (Watts and Dodds, 2007), and climate change awareness (Russill and Nyssa, 2009), which each play a key role in development and low-carbon transition processes.

A further important point is that while agent-based models (ABMs) do not explicitly enforce market clearing, equilibrium prices and quantities often do emerge as the result of agent's buying and selling decisions (Gintis, 2007). This framework consequently allows researchers and policy makers to analyse conditions under which equilibrium outcomes do and don't occur over different time horizons. In addition, in the presence of multiple equilbria, ABMs are powerful tools to understand the probability and process by which economies end up in different states (such as clean vs dirty energy outcomes) (Arthur, 2006; Farmer et al., 2015).

In comparison to CGE and macro-econometric approaches, agent based modeling is still a relatively young and emerging analytical framework. However, its flexibility and intuitive framework for understanding change processes occurring within complex systems has seen it attract increasing interest, particularly within the climate-related literature. Many studies, which compare the relative merits of different approaches for analysing sustainability and climate policy-making, consistently provide strong appraisals and attest to its potential for offering important complementary insights to existing analytical tools (Boulanger and Bréchet, 2005; Bassi, 2014; Farmer et al., 2015; Balint et al., 2017).

However, there are two key challenges currently hindering faster progress and wider dissemination of ABMs within the policy landscape. First, there is a present lack of commonly accepted modeling standards within the ABM community. As a result, the ABM literature is replete with diverse and bespoke implementations, which often use a variety of different programming languages and design structure (Richiardi et al., 2006; Müller et al., 2013). Further, as models (and their output) are often complicated and poorly documented (Angus and Hassani-Mahmooei, 2015; Lee et al., 2015), replicating results or applying existing models to other contexts can be difficult and time-consuming (Richiardi, 2015). Second, estimation, calibration and validation procedures are often particularly challenging within ABMs (Fagiolo et al., 2007). These procedures aim to ensure the model and its parameters are as scientifically robust and defensible as possible. As ABMs often involve a large number of parameters and allow macro-level dynamics to emerge from the interactions and behaviors of micro-level agents, their estimation and calibration can be significantly more involved than other modeling approaches discussed in this chapter.[1]

5 Conclusion

In light of the pressing need to better understand transformational change processes, particularly as they relate to climate and development contexts, this chapter has sought to draw these fields together, highlighting key commonalities and shared learning opportunities.

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[1] That said, calibration and validation of CGE and DSGE models are also subject to criticism. CGE models are often applied to policy analysis without being exposed to any soft of validation process (Beckman et al., 2011; Van Dijk et al., 2016). Calibrating and validating DSGE models is both more challenging and more controversial, as models often require a number of ad-hoc tweaks or 'frictions' to enable them to fit the data (De Grauwe, 2010; Fagiolo and Roventini, 2012)

It is clear that better integration across climate and development domains is paramount – and there are clear advantages for both research and policy. In relation to research, climate and development economists have traditionally studied the process of transformative change in separate fields and with differing emphases. However, identifying key commonalities in respective change processes may not only improve shared learning outcomes, it could also illuminate a more generalized theory of transformational change. For policy, a lack of integration in climate and development initiatives can lead to outcomes that are at best, myopic and at worst, detrimental to their intended objectives.

In terms of methodological tools for analysing and modeling transformational change, this chapter has reviewed four different approaches that have been used in both climate and development contexts. Network analysis provides a useful framework to investigate relationships across economic sectors, and allows scholars and policy makers to better understand technological diffusion and industrial transition possibilities. However, there has been relatively little work on the dynamism of economic networks or to understand how industrial structure may be shaped by policy. CGE models are the standard policy analysis tool in both climate and development fields, and while these models have key strengths when applied to short-term horizons, our review casts doubt on their ability to appropriately capture dis-equilibrium dynamics and emergent attributes of the transformative change process. While macro-econometric models deal better with out-of-equilibrium settings, their strong reliance on historical data weakens their ability to predict fundamentally new and different economic structures and dynamics.

In contrast, the flexibility of agent-based models make them a promising framework for analysing the formation of new economic arrangements and ‘tipping point’ dynamics emerging from complex interactions between heterogeneous agents. If appropriate standards and validation procedures can be progressed and adopted, these models could offer researchers and policy makers an important tool for better navigating and driving the process of transformational change to make simultaneous progress on climate and development goals.

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