SCIENCE POLICY RESEARCH UNIT


SPRU Working Paper Series

SWPS 2019-01 (January)


# Modelling the Evolution of Economic Structure and Climate Change: A Review


Tommaso Ciarli and Maria Savona


Energy Policy

Sustainable Development

Science and Technology Policy

Innovation and Project Management

**Economics of Innovation**

UNIVERSITY OF SUSSEX | BUSINESS SCHOOL

## SPRU Working Paper Series (ISSN 2057-6668)

The SPRU Working Paper Series aims to accelerate the public availability of the research undertaken by SPRU-associated people, and other research that is of considerable interest within SPRU, providing access to early copies of SPRU research.




## Guidelines for authors

Papers should be submitted to swps@sussex.ac.uk as a PDF or Word file. The first page should include: title, abstract, keywords, and authors' names and affiliations. The paper will be considered for publication by an Associate Editor, who may ask two referees to provide a light review. We aim to send referee reports within three weeks from submission. Authors may be requested to submit a revised version of the paper with a reply to the referees' comments to swps@sussex.ac.uk. The Editors make the final decision on the inclusion of the paper in the series. When submitting, the authors should indicate if the paper has already undergone peer-review (in other series, journals, or books), in which case the Editors may decide to skip the review process. Once the paper is included in the SWPS, the authors maintain the copyright.

Websites

UoS: **www.sussex.ac.uk/spru/research/swps**
SSRN: **www.ssrn.com/link/SPRU-RES.html**
IDEAS:**ideas.repec.org/s/sru/ssewps.html**
Research Gate: **www.researchgate.net/journal/2057-6668_SPRU_Working_Paper_Series**

# Modelling the Evolution of Economic Structure and Climate Change: A Review*

Tommaso Ciarli[†] Maria Savona[‡]

**Abstract**

We discuss how different models assessing climate change integrate aspects of structural change that are crucial to improve understanding of the relation between changes in the environment and in the economy. We identify six related aspects of structural change, which have significant impact on climate change: sectoral composition, industrial organisation, technology, employment, final demand, and institutions. Economic models vary substantially with respect to the aspects of structural change that they include, and how they model them. We review different modelling families and compare these differences: integrated assessment models (IAM), computable general equilibrium (CGE) models, structural change models (SCM), ecological macroeconomics models in the Keynesian tradition (EMK) and evolutionary agent based models (EABM). We find that IAM and CGE address few of the aspects of structural change identified; SCM focus on the sectoral composition; and EKM study final demand and employment structure. But all these models are aggregate and omit the complexity of the interactions between structural and climate change. EABM have explored a larger number of aspects of structural change, modelling their emergence from the interaction of microeconomic actors, but have not yet exploited their potential to study the interactions among interrelated aspects of structural and climate change.

**Keywords**: Structural change; climate change; economic modelling

*An earlier version of this paper appeared as part of a report for the Economic Commission for Latin America and the Caribbean (Ciarli and Savona, 2016). We are grateful to Claire Copeland, Luis Miguel Galindo, Gabriel Porcile, Francesco Vona, two anonymous reviewers and editors of the Journal of Ecological Economics special issue, an anonymous reviewer and editors of the SPRU working paper series, and participants at the Eurkind GCW 2016 Conference, the EAEPE 2016 Conference and the Surrey workshop on the economic theory for the Anthropocene (2018) for extremely useful suggestions to improve the paper. This paper has benefited from funding from ECLAC and from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 649186 – Project ISIGrowth.

[†]Corresponding author: t.ciarli@sussex.ac.uk. SPRU, University of Sussex, Jubilee Building, BN1 9SL Falmer, Brighton, UK

[‡]SPRU, University of Sussex, UK; m.savona@sussex.ac.uk

# 1 Introduction

Economic growth is tightly related to several aspects of structural change, such as sectoral composition of output and value added, division of labour, technology of production, industrial organisation and competition, firm size and organisation, and demand composition and preferences.[1] Some changes precede economic growth, others unfold as a consequence of economic growth.

Most (if not all) aspects of structural change influence the short- and long-run relations between economic activity and the natural environment, in ways that are often not predictable, and which are not yet established in the literature (Savona and Ciarli, 2017).

To make things slightly more complicated, the relation is mutual, as changes in the natural environment influence several aspects of structural change (Stern, 2013).

To complicate things one step further, most different aspects of structural change are interrelated, they depend on one another (Ciarli et al., 2010, 2018). For instance, industrialisation and tertiarisation are accompanied by urbanisation (Harris and Todaro, 1970). Economic growth is associated with an increase in the division of labour (e.g. Smith, 1961; Greif, 2006), which changes the relation between industries (Input Output coefficients) and between firms, and modifies the organisation of firms and of production (Lazonick, 1979; von Tunzelmann, 1995). Changes in industries and in the division of labour modify the trade relations among countries, and countries' terms of trade (Prebish, 1950; Singer, 1950; Hidalgo et al., 2007; Cimoli and Porcile, 2013). Sectoral and organisational changes are accompanied by radical and incremental technical changes (Freeman et al., 1982; Mokyr, 2007; Rosenberg, 1974). New and cheaper goods and services must be accompanied by changes in the demand composition (Berg, 2002; Maddison, 2003), social structure and distribution of income. We also expect changes in the organisation of production, trade, technologies, demand and income distribution, to be accompanied by changes in institutions (North, 2005; Chang, 2010; Bowles, 1998), the organisation of societies (McCloskey, 2009), labour markets and employment relations (Lazonick, 1994), and the international economic order (Galeano, 1980).

Therefore, to improve our understanding of the relation between economic growth and environmental impact, we need models that capture: the interactions between different aspects of structural change, at different levels of aggregation; and the interactions between different aspects of structural change and environmental impact (van den Bergh and Gowdy, 2000; Sassi et al., 2010). Focussing on a single aspect of structural change risks to provide a partial understanding of the impact of economic activity on the environment. For example, focussing exclusively on employment shares across industries, we may overlook the role that consumer behaviour (e.g. income, distribution and preferences) may have on these shares, and their effect on, e.g., industrial organisation, technical change, trade, transport. In turn, each of these related aspects of structural change may have a different impact on, for example, emissions.

This paper discusses how different models assessing environmental impact and climate change integrate aspects of structural change that are, we argue, crucial to improve our understanding of the relation between changes in the environment and in the economy. We consider a broad set of aspects of structural change, following Matsuyama (2008) and Saviotti and Gaffard (2008), and building upon the models by Ciarli et al. (2010)–Ciarli et al. (2018). If, as discussed above and more at length in the next section, models should include several aspects of structural change – and their relation, to provide a reliable representation of the impact of economic growth on different aspects of climate change, we assess models on the basis of the number of aspects of endogenous structural change included – and on how their interaction is modelled. Because the interaction of several aspects of structural change imply qualitative changes that cannot be captured by representing a system in equilibrium van den Bergh and Gowdy (2000); Saviotti

[1]See, for example, Kuznets (1973), Berg (2002), Mokyr (2002), Ayres and van den Bergh (2005), McCloskey (2009), Desmet and Parente (2012), Ciarli et al. (2010) and Ciarli et al. (2018).

and Gaffard (2008); Balint et al. (2017) – or moving between equilibria – we find that the family of models that is best suited to capture the interactions between several aspects of structural change and climate change are evolutionary agent based models.

In earlier work, van Ruijven et al. (2008) briefly discuss the extent to which existing 'global' energy models deal with aspects of structural change that are relevant to developing countries. They consider a limited set of aspects of structural change, mostly related to energy, which include: the use of traditional fuels, electrification, (aggregate) sectoral change, income distribution, informal economy, and resource depletion. In an earlier review of models and their account for crucial aspects of environmental sustainability, Köhler et al. (2006a) found that the available models did not include a satisfactory understanding of technological change, particularly with respect to the diffusion of technologies, uncertainty of innovation, path dependency, and heterogeneity of agents and technologies.

We contrast a more complete set of models than van Ruijven et al. (2008), covering different modelling traditions. As in van Ruijven et al. (2008), we do not aim to be exhaustive: we include aspects of structural change that we consider relevant for both economic growth and climate change, and review a sample of models for each group of models.

The paper offers three major contributions. First, based on the empirical evidence surveyed in Savona and Ciarli (2017), we offer a rationale for addressing the complexity of the relations between different aspects of structural and climate change within a modelling framework.

Second, we single out six different aspects, each disaggregated in a number of components (Section 2). Because many of these aspects are related, we argue that they should be integrated within a unique modelling effort, to ensure a proper assessment of the impact of economic activity on the environment.

Third, we review five families of economic models that study the environmental impact of production and consumption (covering the whole population of modelling traditions that we are aware of) (Section 3): Integrated Assessment Models (IAM), Computable General Equilibrium (CGE) models, Structural Change Models (SCM), Ecological Macroeconomics models (in the Keynesian tradition) (EMK), and multi agent and evolutionary models (EABM). For each family of models we discuss the aspects of structural change that they include (endogenise), and their limitations.[2]

Finally, Section 4 concludes the paper.

## 2 Six Aspects of Structural Change and Their Relations with Climate Change

We follow Matsuyama (2008) in defining structural change as a set of interrelated aspects: "[...] complementary changes in various aspects of the economy, such as the sector compositions of output and employment, the organization of industry, the financial system, income and wealth distribution, demography, political institutions, and even the society's value system." Using a similar definition, (Saviotti and Gaffard, 2008, p. 115)[3] suggest that it is not meaningful to model a system in equilibrium "when its composition keeps changing due to the emergence of qualitatively different entities", including all aspects of structural change.

Drawing from those definitions we focus on six related aspects of structural change: sectoral composition, industrial organisation (IO), technical change, employment, demand, and institutions. Although one could easily identify other categorisations, this one has a number of advantages: it loosely builds on previous modelling work, all aspects are related to climate change (Savona and Ciarli, 2017), and was built bringing together related literatures.

[2]See Köhler et al. (2018) for a similar exercise review focusing on sustainability transitions.

[3]"[c]hange in the structure of the economic system, that is, in its components and in their interactions. Components are [...] particular goods or services, and other activities and institutions, such as technologies, types of knowledge, organisational forms etc."

In what follows we discuss how different aspects of structural change may be related to climate change. Table 1 summaries the six aspects, and lists a number of components relevant to climate change for each of them. We also briefly make connections between different aspects, when the relevance of a component to climate change is related to one of the other aspects of structural change.

### 2.1 Sectors

The sectoral composition of an economy influences different aspects of climate change directly and indirectly, through Input Output (I/O) relations, and trade (see also Savona and Ciarli (2017) for a summary). Inputs differ in terms of technical coefficients, labour coefficients, and energy intensity. All three are influenced by other aspects of structural change, such as technical change.

Directly, industries contribute differently to greenhouse gases (GHG) emissions (Stern, 2008) and differ in terms of the cost needed to abate them Enkvist et al. (2007). Indirectly, different industries require different skill sets (Vona and Consoli, 2014), differ in terms of innovative activity (Malerba and Orsenigo, 1997) – level and composition, rents and wages, influencing the distribution of income (which has an effect on climate change through the composition of demand).

We identify five relevant components of the sectoral aspect of structural change (Table 1): sectoral composition, which affect (1) the contribution to GHG emissions; (2) the cost of abatement; (3) sectoral differences in innovative activity; (4) technical, labour, and consumption I/O coefficients; and (5) dematerialisation.

### 2.2 Industrial Organisation (IO)

Closely connected to changes in the sectoral composition are changes in the organisation of production through firms decision to make or buy. Changes in the organisation of production has three main direct effects on climate change. First, increased specialisation is usually associated with higher productivity, which may influence energy intensity. Second, as firms outsource part of the production, they are likely to require more transportation, which is an important component of GHG emissions. Third, outsourcing may come with increased trade, which may imply off-shoring of more or less polluting activities.

Indirectly, the organisation of production may determine market concentration and firm size. In turn, firm size has been shown to be related to the distribution of wages (Bottazzi and Grazzi, 2010; Brown and Medoff, 1989).Changes in productivity across industries may also influence the labour market. These aspects are related to the demand side aspects of structural change. Changes in the organisation of production are also likely to modify the geographic concentration of economic activities and workers, an important factor in the contribution of transportation to GHG emissions.[4]. Finally, changes in the structure of production, geographic and market concentration, and technology life cycle (Abernathy and Utterback, 1978), affect industrial dynamics (Klepper, 1997; Mazzucato, 2002).[5]

We consider five relevant components connected to the structure of production and industrial organisation, which are related to climate change (Table 1): (1) the emergence of new intermediate industries; (2) changes in I/O coefficients; (3) market concentration and firm size; (4) geographical clustering; and (5) industrial dynamics.

[4]See for example Vergara et al. (2013) and GEA (2012, p. 13).

[5]It is important to note that industry life cycles and industrial dynamics are also influenced by the technological regimes mentioned above (Malerba and Orsenigo, 1997), and have been relevant determinants in industrialisation and catching processes (Kim, 1999).

## 2.3 Technical change

Technical change is central both to structural and climate change (Cole et al., eds, 1973; Stern, 2008). It affects the environmental impact of production and consumption in four main ways. First, innovation leads to the substitution of capital and energy for labour, and the the increase in consumption. Second, factor saving environmental innovations (van den Bergh, 2013) may improve the energy efficiency of production processes. Third, via de-materialisation the value added of final goods can be increased, so that consumers gain the same utility from consuming less of a given material good (Ayres and van den Bergh, 2005). Third, by substituting renewable energy sources for fossil fuels (Ayres, 1998; Popp et al., 2010; Stern, 2007).

It is important to distinguish between incremental innovations, which improve energy efficiency, and radical innovations, which require changes in large parts of the economy, including consumer behaviour (below), the production structure (above), and infrastructures (Safarzyńska et al., 2012; van den Bergh et al., 2011), with unindented consequences on the environment (Windrum et al., 2009b). It is also crucial to consider that innovations cluster in time and space, they do not cumulate in a linear fashion (Silverberg and Verspagen, 2007, 2005).[6] The relation between technical change, climate change, and structural change, is not linear: innovation takes time, requires high investments, changes incrementally, has uncertain returns (Nelson and Winter, 1982), and may have a negative impact on climate change in several intended and unintended ways. Uncertainty on the consequences on climate change applies to both 'brown' and 'green' technologies. For example the controversial impact of the cultivation of biofuels, the rebound effect (Stapleton et al., 2015; Steve Sorrell, 2007) and the green paradox (van der Ploeg, 2011; van der Ploeg and Withagen, 2012). Innovation may follow different directions, all with different advantages and disadvantages for the environment (Leach et al., 2010; Stirling, 2009). The direction chosen depends also on the structural institutional aspect of the economy.

We consider seven relevant components that tie technical change to climate change (Table 1): (1) factor bias; (2) clean technologies/energy; (3) radical innovations and changes in paradigms and trajectories; (4) non linear and clustered dynamics; and (7) uncertainties and unintended effects.

[TABLE 1 HERE]

## 2.4 Employment

Production structure, firm organisation and technologies influence also employment and its compensation.[7] For instance, employment relocates across industries and geography, and the new industries and technologies demand for new skills and novel combinations of know-how (Vona and Consoli, 2014; Consoli et al., 2016). The pace of adaptation of the labour market to new industries, geographies, technologies and tasks, may induce a more or less efficient transition towards green technologies – or impede it.

Indirectly, changes in employment are likely to affect the distribution of wages (Brynjolfsson and McAfee, 2014), which has an important effect on the demand composition (more below).

We consider five components of the employment aspect of structural change, which are related to climate change (Table 1): (1) green jobs and changes in the skill sets; (2) unemployment; (3) distribution of wages; (4) changes in the labour intensity across industries; and (5) labour composition across industries.

[6] This dynamics can also be interpreted through the lenses of long waves (Freeman et al., 1982), particularly if we consider that the latest of these waves may be around environmentally friendly technologies (Freeman, 1996), and socio-technical transitions (Köhler, 2012).

[7] The implications of a green transformation for the job market are still not well understood, due to the multiple compensation effects (Dierdorff et al., 2009; IEA, 2009; Martinez-Fernandez et al., 2010).

### 2.5 Demand

On the demand side there are two main aspects of structural change that are crucial to climate change, and which are related to aspects discussed above.

First, income distribution.[8] Income distribution shapes the level of final consumption through savings (Dynan et al., 2004), the distribution of consumption across industries (Aguiar and Bils, 2015),[9] aversion to pollution (Greenstone and Jack, 2015) and a country's capacity to generate environmental innovations (Vona and Patriarca, 2011).

Second, and related, consumer preferences change with income and over time (Witt, 2001, 2011). They can create an incentive to innovate towards greener, or cheaper goods (Janssen and Jager, 2002; Windrum et al., 2009a,b).Preferences have been discussed extensively with respect to time: risk aversion and the rate at which individuals discount future generations' consumption and cost of climate change, relative to present consumption and costs to reduce emission Stern (2013); Pindyck (2013); Nordhaus (2013).

We consider three broad components related the demand aspect of structural change (Table 1): (1) income distribution; (2) consumption preferences; and (3) preferences for direct and indirect effects of environmental degradation, current and future.

### 2.6 Institutions

Several components of the aspects of structural change just discussed are influenced by institutions shaping policies (Arrow et al., 1995), incentives, social structures, and interactions (Arrow et al., 1995; Boulanger and Bréchet, 2005; Greenstone and Jack, 2015; Fagerberg et al., 2016).

Innovation systems can help identify the main institutional weaknesses in harnessing environmentally friendly technology Jacobsson and Bergek (2011). As discussed with respect to technological trajectories and pathways, agency and power are crucial in determining the transition towards more environmentally friendly socio-technical regimes (Smith et al., 2005; van den Bergh et al., 2011).

Because of the complexity of defining, measuring and stylising institutions, they are also the most problematic aspect to model. We consider the following components of the institutional aspect of structural change related to climate change (Table 1): (1) appropriation regimes and property rights; (2) technological opportunities; (3) access to resources (power relations); (4) governance (power relations); and (5) social interactions.

## 3 A Review of Economic Models

In this section we briefly discuss how the main modelling traditions that investigate the relation between the economy and climate change include one or more of the aspects structural change. We review, in turn, IAM and CGE models (Section 3.1), models that focus on sectoral change and build on the structuralist tradition in economics (Chenery et al., 1984; Palma, 2008), which we call structural change models (SCM) (Section 3.2), the recent ecological macroeconomic models in the Post Keynesian tradition (EMK) (Section 3.3),[10] and evolutionary agent based models (EABM) (3.4).

For each modelling tradition, we briefly summarise the main features of the models.[11] We

[8] E.g. related to the organisation of production and firm size (Ciarli et al., 2010), off-shoring of part of the production, distribution of skills (Consoli et al., 2016), and investment in (green) capital and the distribution of its rents (Rezai et al., 2013).

[9] Which can be more or less polluting.

[10] We do not consider econometric approaches which combine I/O and post Keynesian features, such as E3MG (Köhler et al., 2006b) or FIDELIO (Kratena et al., 2013), because they are developed mainly for estimation purposes.

[11] For reasons of space we do no proper justice to any of the models, especially for IAM and CGE models for which a large number have been produced and assessed (and for which a large number of excellent reviews exist).

then discuss how these models account (or not) for the six aspects of structural change. A sketched summary of this discussion for all models is presented in Table 2. Table 3 provides a more detailed check-list of which of the components discussed in Section 2, and listed in Table 1 is included in the different classes of models.

## 3.1 Integrated Assessment Models (IAM) and Computable General Equilibrium (CGE) Models

### 3.1.1 IAM

Since Nordhaus (1979), a large number of IAM have been developed to study the impact of economic activity on climate change, and the economic costs of reducing the environmental impact of production and consumption.[12]

Stern (2008) and Pindyck (2013) summarises the linear cycle stylised in IAM between the environment, social and economic factors in the following 6 steps: (1) consumption and production decisions generate GHG; (2) the GHG flow is transformed in a stock accumulated in the atmosphere; (3) this stock traps heat and generates global warming at a given rate; (4) warming induces climate change; and (5) climate change has several effects on individuals and the environment (damage function), which are quite complex to capture and assess; (6) GHG flow and stocks may be abated with a given cost which depends on present and future costs of climate change, the present cost of abating GHG emissions, and time preferences.

Despite their great contribution in understanding some of the relations between present economic activity, environmental impact, and its costs on future economic activities, IAM have a number of limitations that need to be addressed before they can become a reliable tool to assess policies for sustainable growth (Stern, 2013; Pindyck, 2013; Stern, 2016). In particular: (1) the drivers of growth are exogenous, unaffected by climate change – climate change may have permanent effects on the stock of capital; (2) there is no account of radical uncertainty (Weitzman, 2011, 2009, 2014);(3) few IAM consider probability distributions of risks; (4) the assumptions about social welfare based on the estimation of the risk aversion to future changes, and of the discount rate; (5) limited attention to technological change which may reduce the costs of future mitigations via the use of renewable resources, or reduce the use of energy (Ackerman et al., 2009).[13]

In recent reviews, Farmer et al. (2015), Mercure et al. (2016), and Balint et al. (2017) discuss more substantive limitations, with respect to the complexity of climate change, its relations with the real and the financial economy, and the relevance of incorporating the interactions between different economic agents.

#### Aspects and Components of Structural Change

The extent to which IAM capture different aspects of structural change is limited (Tables 2 and 3). First, they account for limited differences across macro sectors of the economy, at an aggregate level, distinguishing only between sources of energy use. The cost of reducing GHG emissions depends on the industrial composition, and its use of resources (e.g. transport and energy efficiency, and land use) (Stern, 2008), but the relative growth of different industries and macro sectors is not endogenised and I/O relations do not change.

Second, when endogenised, technical change is modelled as a linear learning by doing (LBD) or by an aggregate R&D function (see Popp (2004) and reviews in Köhler et al. (2006a), Gillingham et al. (2008), and Popp et al. (2010)). Because these changes occur at the margin (Ackerman et al., 2009), they normally represent a reduction in the energy use but have no effect on the structure of the economy.

[12] Wei et al. (2015) perform a basic bibliometric exercise that describes the extent and distribution of research on IAM.

[13] See Farmer et al. (2015) for a short discussion of technological change in IAM.

Third, IAM assume full employment, and changes in wage, skills, or (green) jobs are not considered, to our knowledge.

Fourth, on the demand side IAM include time preferences of the representative agent, which in more sophisticated models change with the impact of GHG. Although time preferences are a relevant aspect of consumption related structural change that a model should consider, they are likely to depend on other state variables as well, such as income, not included in IAMs.

Finally, no endogenous changes in the rules, regulations, or distribution of power is considered in IAM. Policies are introduced exogenously, and used to contrast their effect on costs and benefits of abatement.

### 3.1.2 CGE

A large number of CGE model have been adapted to run integrated assessment in a framework of multiple macro sectors in equilibrium (market is cleared in each period) (Boulanger and Bréchet, 2005). These are complex models with a large number of regions and industries, connected to the environment through the use of various energy sources and GHG emissions. Figure 1 depicts the three main markets of a typical CGE: labour, capital, and goods.

[FIGURE 1 HERE]

Figure 2 shows an example of the full structure of a CGE model with several economies, industries, and energy inputs. Policy instruments addressing the incentives for different macro sectors of the economy (such as taxes) are assessed with a number of environmental indicators.

[FIGURE 2 HERE]

A standard CGE is composed of three main groups of agents: households, firms, and the government, plus the rest of the world (RoW in Figure 1).[14] Households pertain to different economic groups, but each group is composed by a representative household maximising an inter-temporal utility function to find the optimal combination of savings and consumption. Households buy from different industries durable and non durable goods, produced domestically or imported. Households' budget constraint is determined by their wages (via the labour market equilibrium), savings, taxes, and transfers. The sources of energy consumption for households are: fuel for transport, electricity and heating. To account for the rebound effect, energy is a nominal service the demand of which depends on service prices (for more energy efficiency, a lower price would command a higher demand).

Firms maximise profits, subject to the available capital stock and technology, using labour,[15] capital, intermediate inputs, and energy sources. Models may differ with respect to the energy sources included, how they are converted in energy use and how these are converted into GHG emissions. Models usually have one representative firm per industry. Input quantities depend on factors demand, which depend on their prices. Capital, labour, and energy prices are usually determined exogenously. Technical change is modelled for each input individually, modifying the composition of inputs (factor biased), and as a change in Total Factor Productivity (TFP). Technical change is usually semi endogenous, mainly driven by LBD. The model dynamics is a result of investment in new capital (through savings).

In the labour market, households and firms bargain the number of working hours – depending on the amount of leisure that households want to consume in the present and in the future, determining the equilibrium wages (using efficiency wages). Voluntary unemployment is then determined by the choice of households and market frictions. Labour supply may change with population characteristics, which evolve exogenously.

[14] We follow Capros et al. (2013).

[15] Which may be divided between skilled and unskilled.

The I/O coefficient define the flow of goods and money between industries, including a number of intermediate industries, final demand for durable and non durable goods, imports, and exports.

The models are closed by the public sector collecting taxes and paying benefits (mainly to unemployed) and interests.

CGE models are calibrated with data on consumption, industries, investment, wages, trade, taxes and transfers, I/O coefficients, and GHG emissions. Models are then simulated for a number of periods to assess the environmental outcome, in equilibrium, for different policies that affect households', firms' and government's objective function.

**Aspects and Components of Structural Change**

The extent to which CGE capture aspects of structural change and their interaction improves with respect to IAM, but is still limited (Tables 2 and 3).

First, these are multi-sector models. The contribution of each industry to output is given by calibrated I/O coefficients. However, changes in the division of labour is not contemplated and I/O coefficients are fixed through time. (with the exception of some models introducing a semi exogenous LBD).

Second and related, different industries contribute differently to GHG emissions, and may be produced domestically or imported, but the only endogenous change in the intermediate demand, is due to LBD or continuous and monotonous directed technological change.[16]

Technical change, therefore, is modelled in a way similar to IAM: changes occur at the margin, as improvements in energy efficiency or GHG emissions.

Fourth, on the demand side different groups of households have different incomes, and may have different preferences for goods' prices. But these preferences do not change with time, satiation, or emergence of new goods (no new goods emerge). Consumption patterns change as a function of income, representing a relevant aspect of structural change. When changes in labour markets and urbanisation are included in CGE, they are considered as exogenous, such as in O'Neill et al. (2012).

Alike IAM, CGE models account for institutions as exogenous policies that may be implemented to reduce GHG emissions. No institutional aspect is represented.[17]

[TABLE 2 HERE]

## 3.2 Structural Change Models (SCM)

In this section we group a number of models that explicitly investigate structural change as change in the employment shares across industries, and which are influenced by the structuralist tradition in economics (Chenery et al., 1984; Palma, 2008). Unlike IAM and CGE models, we could find a limited number of relatively different SCM. To capture these differences, we briefly discuss the main features related to aspects of structural change and climate change for a sample of models.

Campiglio (2014) models a representative household consuming a green service and a standard good, which requires to use also a common resource, the environment. The standard good benefits from the public investment in infrastructures, whereas the green service does not. Results suggest that structural change towards the green service occurs only when households

[16] One exception is Sassi et al. (2010), who use a fixed coefficient production function, and model changes in final uses of energy and transportation. Bosetti et al. (2009) include radical innovations in the WITCH model, but this is the outcome of linear research and development and learning effort at the aggregate level, with *ad hoc* timing and pricing.

[17] This is a limitation that may impossible to address within CGE models, which rest on the assumptions that market can always clear, and therefore there is no need for other institutions to regulate them, or an economy more at wide (Scrieciu, 2007).

have a lower preference for the manufacturing good, or when the ratio of public versus private investment is larger than the long run equilibrium level. Higher rates of public investment have a negative effect on welfare because they increases private capital reducing the common resource (environment).

Antoci et al. (2012) study how the dynamics of sustainability in developing countries is affected by changes in the sectoral composition, in the presence of natural resources that can be exploited by different agents, and put to different uses. Their model represents a small open economy with two industries, a traditional industry based on the use of natural resources, and a manufacturing industry (with a representative firm for each industry). Both industries use natural resources to produce output. The main difference is that the traditional industry cannot substitute machines for natural capital, while this is possible in manufacturing. The model has two different agents: the 'poor', who depend on self employment using natural resources, or who are employed by the 'rich'; and the 'rich', who invest in new capital. Structural change involves the poor agents only. They can either remain in the traditional industry, using the natural resource, or work in the modern industry, for a salary. This can occur only because of exogenous changes: (1) increase in the productivity of the modern industry; (2) increase in the environmental impact of either industry; (3) reduction in the carrying capacity of the natural resource (availability).

Both models address and illustrate two interesting aspects of structural change and environmental impact, respectively related to tertiarisation and the exploitation of natural resources, but do not provide further elements *on* the modelling of endogenous structural change.

Pasche (2002) proposes a stylised model of sectoral change that follows an evolutionary process, showing that technological and sectoral change have only a short run effect on the reduction of emissions. To abate pollution in the long run the economy has to converge either to lower consumption or to zero growth. Bretschger and Smulders (2012) consider the effect of both sectoral change and innovation on the use of resources in a model in which workers can move across industries with different rates of innovation. Contrary to Pasche (2002), they find that structural change can complement technological change in achieving sustainability, even when there is no alternative to non-renewable resources to produce energy (low substitutability between renewable and non-renewable sources of energy). The use of natural resources for producing energy pushes structural change, which together with innovation in the different industries allows the economy to keep growing. van der Meijden and Smulders (2018) find that the availability of renewable technologies provide an incentive for more R&D and investment, contributing to growth and to the transition from non renewable to renewable sources of energy. Their results are in contradiction with models assuming that the reduction in the availability of energy sources should reduce incentives to innovate and invest in other activities (due to the difference in prices).

Pan (2006) extends the analysis to more than two industries, vertically integrated, and introduces technical change in the I/O coefficients. New technologies are the result of endogenous technical change through investment in a dynamic I/O model. The model is quite aggregate and assumes a stylised dynamic of technical change, but it is an important step towards considering two fundamental and related aspects of structural change: technological change and the organisation of production.

Ayres and van den Bergh (2005) introduce further aspects of structural change and their relation with environmental impact. Focussing on the substitution of production factors, they identify three main steps of endogenous growth that allow to sustain exponential growth. First, changes in inputs and LBD (use of fossil fuel resources). As fossil fuels substitute human energy, they increase productivity, save time and labour, reduce prices, increase demand and induce more use of fossil fuels, reducing its costs via learning (a simplification of technological change). Second, industrial organisation and final demand (division of labour and learning). Vertical specialisation increases productivity, through technological change, economies of scale and LBD, reducing prices and increasing consumption. The increase in consumption has to be accompanied by product innovations that push upwards Engel curves. Third, radical innovation and demand (de-materialisation). This mechanism operates through an increase in the value added of final goods, so that the number of goods produced can decrease, moving to services that replace them. In order to generate sustained endogenous growth the new services must command new demand.

**Aspects and Components of Structural Change**

Most SCM focus on sectors (employment composition) and demand components of structural change (see also Tables 2 and 3). Most are two sectors models (polluting and non polluting) where changes in the allocation of labour across sectors depends on output cost, which depends on scarcity or the negative externalities it generates and on exogenous factors such as technological change and policies.

A couple of models also introduce industrial organisation, such as changes in the I/O structure (Pan, 2006), and technical change in the form of radical innovation, such as the emergence of new intermediate industries leading to de-materialisation (Ayres and van den Bergh, 2005).[18]

With respect to employment, these models focus only on sector shares (labour composition), which in a couple of models may imply changes in income. Changes on the demand side are contemplated only in Antoci et al. (2012) (income distribution between two classes of consumers) and Ayres and van den Bergh (2005) (satiation which leads to technical change).

Endogenous changes in institutions, as for IAM and CGE models, are not contemplated, but are used to study alternative scenarios.

## 3.3 Ecological Macroeconomics (Post Keynesian) (EMK)

A number of recent papers integrate ecological issues (biophysical limits) and post-Keynesian macro models (macro balance constraints and demand driven) in what has been called ecological macroeconomics (Jackson, 2009; Jackson et al., 2014; Rezai et al., 2013; Rezai and Stagl, 2016).

Hardt and O'Neill (2017) summarise their main features in a recent review. Models tend to include the following six macro sectors related through monetary transactions: households, firms, banks, government, central bank and the 'rest of the world' (Jackson et al., 2016). An increasing number of these models model these relations in a stock flow consistent (SFC) framework (Lavoie and Godley, 2001), which echoes the stock and flow constraints characterising natural resources, and which allows to model the relation between environmental instability and financial instability in the economy (as part of the damage function). Models do not assume full employment, allowing to study the relation between environmental constraints, negative growth rates, and consequences on the real economy. Some of the models are multi-industry and include I/O relations similar to those discussed for CGE models (inputs requirements are assumed constant), and industry-specific emissions. Figure 3 shows an example of one of the richest EMK model, which is multi-industry, SFC, includes different energy sources, and three classes of households (capitalists, workers, and unemployed).

[FIGURE 3 HERE]

The environmental damage is usually modelled exploiting the multi-industry I/O structure together with the differentiated sectoral impacts, or by assuming different energy sources. Only a small number of models integrate the feedback from the environmental degradation to macro economic outcome.

The main contributions of these models are the inclusion of financial balances, to account for the relation between financial and environmental instabilities, and (aggregate) employment

[18] With respect to technical change, Pan (2006) does not go much beyond exogenous dynamics and the already discussed factor saving learning curves and innovations.

dynamics. Stock flow consistent models are useful to study how indebtedness in some macro sectors of the economy (firms, households, banks) may impact on other macro sectors, and defines constraint in the economic system (households demand and investment behaviour) that are similar to those in the environment. The attention to employment makes it possible to focus on the relation between changes in productivity, wages, and working hours, for example in the context of reducing output and employment to reduce the impact on the environment. For instance, Rezai et al. (2013) argue that reducing working hours may have counter-intuitive effects at the aggregate level, by tightening the labour market, increasing workers' bargaining power, and increasing wages, which may provide an incentive for firms to increase capital investment and productivity. This, in turn might have a negative effect on climate change (increasing energy use), ambiguous effects on unemployment, and increases capital output. Rezai et al. (2013) also warns against a shift towards more productive industries, which may also have undesired effects: cross country estimates show that the increase in productivity is related to increases in energy use (60%) and only partially to an increase in energy efficiency. In other words, energy efficiency alone can mitigate only partially the ecological impacts of increases in output. One of the reasons for this is the existence of a rebound effect also at the macro level in a framework in which there is non voluntary unemployment. This is explained by an increase in expenditure in green technologies to increase energy efficiency, which would also increase output and therefore energy consumption (independent of households income and energy price, which is the rebound effect at the micro level).

Related to employment, some EMK models integrate the functional distribution of income, with some models distinguish capitalists and wage earners (e.g. Figure 3). However, no other differences in income are considered, and classes' population does not change. Jackson et al. (2014) propose to include income distribution in EMK models, for example to test if lower growth increases the capital share of an economy, inducing more inequality, use of energy, and of natural resources.[19] But so far this remains in the agenda.

#### Aspects and Components of Structural Change

Rezai et al. (2013) suggest that EMK models can address some of the preoccupations of ecological economists, such as adaptive and bounded rational behaviour, income distribution, macro rebound effects, and de-growth scenarios (reduced consumption) which may lead to unemployment (see also Tables 2 and 3).

They account for short run disequilibria (and feedback loops in the case of system dynamic models (Jackson et al., 2016)), which characterise structural change. However, EMK models account for a limited number of components of structural change. With respect to employment, they include unemployment consequences of investment decisions, in some cases across different industries. With respect to industries, they endogenise changes in the environmental impact of economic activity through investment decisions that depend on the financial accounts of the economy. Similarly, the final demand may change following households indebtedness and financial instability, but they considered mainly aggregate demand, at most divided into two classes.

Less developed, so far, are changes in I/O relations between industries,[20], the industrial organisation, including different sources of energy, and technical change, which is totally missing – not necessarily by chance (Rezai and Stagl, 2016).

Similarly to earlier models, there is no reference to institutions, except from exogenous policies and scenarios, and non-voluntary unemployment.

[19] Jackson and Victor (2016) show that this is not necessarily the case.

[20] A more focussed contribution, Kemp-Benedict (2014) builds a neo-ricardian model to study the role of primary resources on economic growth. The model represents three vertically integrated industries, whose contribution to growth is measured by a mark-up on the cost of external inputs, to analyse how changes in the demand have different effects on primary, circulating and wage components.

While promising, the current state of modelling in EMK models/proposals does not offer many more elements to account for structural change than those presented in advanced CGE models and SCM, a part from employment and investment instability.

### 3.4 Evolutionary Agent Based Models (EABM)

It is unlikely that modifications to the aggregate models discussed so far (including micro-founded models relying on the representative agent, such as CGE) may add substantial aspects and components of structural change, and their interactions with climate change. This is because most aspects depend on the interactions within and between populations of heterogeneous agents, and how these interactions change over time and under internal and external pressures Farmer et al. (2015).

To properly examine the relation between economic activity and the natural environment we would benefit from models that (van den Bergh and Gowdy, 2000): 1) consider competing and mutating states of the economy, rather than a single optimal state; 2) allow for irreversibility – any economic action has an impact on the system, not a mere experiment that can be retracted; 3) depart from marginal variations, because changes in species and components of structural change have multiple impacts whose interactions is not possible to predict from a single function;[21] 4) include threshold effects – systems may reach tipping points that induce radical changes, which are usually not reversible; 5) include evolutionary processes of selection, mutation (innovation) and retention, which explain both ecological and economic dynamics (Nelson and Winter, 1982).

Evolutionary economics has studied some of the aspects of structural change discussed in this paper, modelling the co-evolution of traits (e.g. preferences), agents and populations at different levels (e.g. workers and firms), the emergence of new activities and the transition to new technologies. Agent Based Models (ABM) have been successfully used to study (Balint et al., 2017) out-of-equilibrium dynamics, crises and tipping points emerging from the interaction between several heterogeneous agents; they integrated agents that adapt, mutate, form preferences, reproduce, and influence other agents' preferences and behaviour in a way that is not predictable looking at the behaviour of the single entity (Arthur, 2013), or directly at the aggregates (Beinhocker, 2006; Tesfatsion and Judd, eds, 2006).[22]

We focus on macro models that represent the whole economy, because they are comparable to models discussed so far. Due to the substantial differences in modelling strategies, we summarise the main features related to aspects of structural change for a number of models. Unless differently specified, all models are micro based, and study macroeconomic dynamics as an emerging property of interactions among agents and populations (Tesfatsion and Judd, eds, 2006). We briefly summarise micro models that focus on specific macro sectors of the economy at the end.

Wolf et al. (2013) (Lagom RegiO), based on Mandel et al. (2010), embody several aspects of structural change. Sectoral composition may change through time, as a result of technological change and demand composition, influencing the contribution to GHG emissions. I/O relations between industries may also change as a result of innovation and imitation. Changes in IO include industrial dynamics and the distribution of firms' size. These are result of induced technical change and LBD, incorporating structural process such as the emergence of radical innovations and technology clustering (through imitation). The model also includes related

[21] For instance, it is impossible to compute the value (or the effect) of one species that goes missing: species are interconnected in a complex system, and it is not always possible to assess what happens to the rest of the system when they mutate.

[22] Further discussion on the comparison between models in the neoclassical tradition and agent based and evolutionary models see Scrieciu et al. (2013) and Giupponi et al. (2013). For a broader discussion on the major differences between multi agent models and CGE models, in particular DSGE models, see Fagiolo and Roventini (2012).

changes in employment and final demand. Households looks for jobs in their and neighbouring regions (migration). Labour supply and innovation (when labour saving), together with labour demand across regions determine unemployment and wages, affecting income distribution. Other components of structural change on the demand side includes household imitation of their neighbours, which changes the aggregate composition of demand across firms and industries. The environmental impact simply depends on the fuel used for production, which differs across industries, and has no feedbacks on the economy.

Gerst et al. (2013) (ENGAGE) based on Dosi et al. (2010), accounts for aspects of structural change mainly related to firm innovation in the capital good and the energy industries. Capital good firms produce capital vintages used by final good firms, and define a number of features for the rest of the economy: (1) the productivity of final good firms; (2) the energy required to produce the final good; (3) the energy required to produce the capital good; and (4) the energy intensity of final goods, which affects firms market shares, their prices, and therefore the distribution of final goods with different energy intensities in the market. Emissions depend on capital vintages (technical change) and the type of energy produced. The energy industry includes firm producing energy and firms producing the technology to produce energy. Energy producers buy technologies from the technology producers, and each technology has a different price, productivity, and environmental impact. There are three technologies that can be produced: carbon heavy, carbon light, and carbon free (renewable). The substitution of cleaner technologies for more polluting ones is based on earlier models (Grübler et al., 1999; Ma and Nakamori, 2009; Robalino and Lempert, 2000). Other changes in industrial organisation include firm size and market concentration. Another important component related to technical change is the uncertainly of the innovation process, which depends on firm sales and the investment in clean energy, endogenous to firm behaviour. Energy intensity also changes the cost of consuming goods, and households choice.

Desmarchelier and Gallouj (2012), also built on Dosi et al. (2010), study the relation between technical change, dematerialisation and changes in consumption patterns. Similarly to some SCM, they model changes in the sectoral composition of output from manufacturing to services, characterised by different GHG emissions. Structural change in sectoral composition is related to changes in employment (between the two industries) and consumption shares of heterogeneous consumers which evolves over time following Engel curves which are function of wages (which also differ across the two industries): as wage increase, households substitute manufacturing goods for services. Technical change occurs mainly as changes in capital vintages, induced by a tax on emissions which puts a selection pressure on more polluting firms.

Monasterolo and Raberto (2016) is an interesting mix of macro system dynamics (as in some EMK models) and agent based modelling, and can represent an interesting bridge between the two traditions. They study the effect of green fiscal policies and monetary policies on firms' investments, unemployment, wages, credit market and economic growth. They account for aspects of structural change related to employment and demand through income distribution. They model the relation between technology and (green) skills, which has an effect on the distribution of wages. The model also represent two classes of consumers. Income distribution is related to green investment through the equity shares owned by the capitalists.

Lamperti et al. (2017), also based on Dosi et al. (2010), is the first ABM (we know of) that introduces an explicit damage function, providing a fully fledged ABM alternative to IAM and CGE models. The main, crucial, new aspect of structural change, with respect to models discussed so far, is the feedback impact of climate change on the structure of the economy via GHC induced shocks. From an EABM perspective, environmental shocks may change the structure of the economy because their impact may vary across populations and between agents within populations (agents are exposed to a different extent or may be more or less resilient). For instance, climate shocks may change the composition of industries, as their impact on firms' labour productivity, energy efficiency, capital stock, and inventories differs across industries.

Ponta et al. (2018), based on the EURACE model (Cincotti et al., 2010; Teglio et al., 2017), study the transition from fossil fuels to renewable energy. The main addition with respect to earlier EABM is related to sectoral composition and IO. They introduce a foreign provider of oil, which affects the cost of intermediate and final goods (through the fossil fuel energy source).

Nannen and van den Bergh (2010), based on Nordhaus (1992), is the only EABM (to our knowledge) that considers components of structural change related to institutions. The model represents different countries that decide whether to invest in more or less polluting technologies. Countries' decision evolves through time via mutation and imitation. Imitation occurs by observing the performance of neighbours' adoption choice in the past. However, countries make errors in imitating (because of limited information). Policy makers can use these errors to induce agents to invest in one or the other technology.[23] They cover three relevant components related to institutions: changes in the structure of production due to changes in the technologies (also covered by the models above), path dependency due to network externalities, and the effect of social interactions, a crucial component aspect of the institutional aspect of structural change.

### 3.4.1 Innovation Models (Micro)

Several EABM offer insights on the complex relations between technological change and climate change (see also Balint et al. (2017)), focussing on specific micro aspects, while ignoring the rest of the macro economy. They provide a good understanding of the incentives and behaviour of firms, consumers and other actors, and how they may contribute to radical innovations that accompany environmentally friendly transitions. Several of these models were reviewed in Safarzyńska et al. (2012).[24] We briefly discuss the main aspects of structural change that they study.

Oltra and Saint Jean (2009) study the relation between industrial organisation and demand components focussing on how technological regimes and demand conditions influence industrial dynamics and the consequent emergence (or lack of it) of technological designs with environmental features.

On technical change, Zeppini and van den Bergh (2011) study the emergence of radically new technologies from the recombination of existing technological trajectories that are close substitute – clean and dirty – which may lead to 'hybrid' technological pathways. Windrum et al. (2009b,a) use an NK model (Kauffman and Levin, 1987) to study the relation between technological complexity, demand preferences, and the emergence of radically new technologies.

Several models have studied the co-evolution of technologies consumer preferences on the demand side. Windrum et al. (2009b,a) study consumers' influence in creating incentives to invest in green technologies, and how this influence depends on income distribution, peer pressure, and firms' strategy in attracting consumers with non green product features. Safarzyńska and van den Bergh (2010a) extend that model to analyse policies on the supply (tax) and demand side (campaigns promoting green technologies). Buenstorf and Cordes (2008) analyse the role of consumers learning on the diffusion of green technologies. And Bleda and Valente (2009) study the role of eco-labelling on consumer demand and firm innovative behaviour.

Institutional components of structural change are less regarded also in micro models. Safarzyńska and van den Bergh (2010b) study the role of institutional changes on the use of natural resources and on the implementation of environmental policies. In a multilevel model of group

[23] Janssen and de Vries (1998) find similar results adding agents with different views of the world to a standard aggregate model. The different views affect the way in which changes in the environmental impact are perceived, and affect the response to environmental policies. As agents learn from each other, and the share of the population with different views changes, the response to environmental policies is also affected.

[24] Cecere et al. (2014) provide another review of green innovations from an evolutionary perspective, referring to both empirical and theoretical studies, and focussing mainly on the role of path dependency and lock-in. While Faber and Frenken (2009) is an interesting collection of evolutionary models targeting environmental economics, innovation, and policies.

selection they investigate how different forms of power modify the pay-offs distribution for different groups, and their influence in determining the future behaviour of the economy (and related ecological choices).

**Aspects and Components of Structural Change**

EABM relax three basic assumptions of the models discussed earlier (Sections 3.1-3.3): aggregate behaviour (or average behaviour in the case of microfoundations in CGE models), perfect rationality of heterogeneous interacting agents and out of equilibrium dynamics.[25] As a result, they provide insights on the relation between several aspects of structural change – in the populations, the state of the system (not necessarily in equilibrium), more or less radical technologies, non reversible technological structures – and climate change.

At the sectoral level, we have discussed models that study changes in the sectoral composition (each industry with different contributions to GHG emissions) via innovation and I/O coefficients.

With respect to IO, models introduce industrial dynamics and changes in firm size, and to a limited extent chancing composition of energy sources, and geographical concentration.

The most detailed aspect of structural change is technical change, with models endogenising research of cleaner technologies through R&D, and some models introducing radical innovations, non linear, clustered and random features of innovation, and the uncertainty related to the discovery of new technologies.

With respect to employment, EABM have endogenised labour markets, unemployment, wage differences, green skills and industries with different labour intensities.

The demand side aspects of structural change have also been introduced, endogenising income distribution, and its impact on consumer preferences (which change via imitation and mutation) and consumption shares.

EABM have also integrated, although only partially, relevant institutional elements of structural change, focussing on the structure of interactions among decision makers.

More recently EABM have also introduced the reverse effect of climate change on some components of structural change through diversified shocks on different sectors of the economy.

Some of the microeconomic aspects of structural change have been developed more exhaustively in micro models that focus on environmental innovations and technological transitions. These are industrial organisation, technical change, demand, and institutions. However, these models lack the feedback with the other macro sectors of the economy.

[TABLE 3 HERE]

# 4 Discussion and Concluding Remarks

In order to improve our understanding of the relation between economic growth and environmental impact, we propose that it is crucial to understand the interactions between several aspects of structural change that accompany economic growth, and climate change. In Savona and Ciarli (2017) we discuss more at length the empirical evidence on some of the aspects of structural change. Assuming away these aspects of structural change in macro and policy models may lead to wrong outcomes and predictions. For example, how do changes in the composition

[25] The extension to multiple equilibria (Wolf et al., 2016) is marginal improvement with respect to the analysis of the interaction between different aspects of structural change and climate change. Structural change, as discussed in this paper, refers to continuous processes from relatively stable conditions in the short term to different relatively stable conditions. Multiple optimal equilibria offer different potential outcomes, but does not improve our understanding of how interacting aspects of structural change move the system from one potential equilibrium to the next (which may well cease to exist during the transition process).

of industry relate to changes in firm size, employment, wages, income distribution, and therefore on consumption preferences? Because different industries have a different impact on GHG, consumers purchase different goods, demand changes with income distribution, all these aspects will matter for GHG. Because they influence one-another, modelling their interaction is crucial.

We found that different modelling traditions include aspects of structural change, their interactions, and the interactions with climate change to different degrees (Tables 2 and 3).

IAM account for some sectoral differences, distinguishing between sources of energy use, but the relative growth of these sectors is not endogenised; industrial organisation is not relevant; technical change is modelled as marginal changes in an aggregate production function through LBD; and the main changes in the demand are time preferences.

CGE models include a larger number of industries, related through I/O coefficients, with different learning curves and contributions to emissions, but these relations are fixed; they also include different consumption patterns the average representative consumer, which also doe snot change.

These models allow to analyse the effect of different sectoral compositions, relations, and consumption preferences, but cannot integrate structural change as part of the model dynamics. Three main assumptions make their use problematic to account for more, relevant, components of structural change (and their relation with climate change). First, perfect rationality (even under limited information) does not allow for true uncertainty, which characterise the impact of economic activities on the environment, sometimes in the form of unintended consequences. Second, in the absence of a distribution of agents, with different characteristics, preferences, and behaviours, which influence each-other, and with different influence on the system, there is no scope for structural change. Third, under the market clearing framework in which there is one unique equilibrium along which an economy grows it is not possible to capture "the emergence of qualitatively different entities" (Saviotti and Gaffard, 2008, p. 115). Even with multiple equilibria, it is not possible to model the transitional adjustments (Barker, 2004) that are at the corer of structural change.[26]

SCM focus on the I/O interaction between industries, and how they may change due to climate change. However, we found only a couple of models that introduce also changes in the I/O coefficients and model the emergence of new intermediate industries. Differences on the demand side are not more sophisticated than those already included in CGE models.

EMK models integrate ecological unbalances and monetary unbalances in a unique macroeconomic frameworks, to study the relations between ecological and macro economic balance constraints. Although models are demand driven, there is no structural change on the demand side. The main contribution is in the analysis of the nexus between (un)employment dynamics, investment, environmental impact and economic growth.

To account for related aspects of structural change, and their interactions with climate change, we need to model evolving complex systems (Costanza et al., 1993). We must represent systems that are out of equilibrium, and subject to competing dynamics that depend on their behaviour, and on their interaction with similar agents. We must consider economies in which: (1) the relevance of industries change across time and space and where firms in different industries behave differently and have different incentives; (2) the relation between industries also change constantly, affecting industrial dynamics, size, trade and transportation; (3) technical change is a complex process *per se*, which involves non measurable risks, investment, radical shifts and non reversible choices, and which determines future technical advances; (4) shifts in industries, industrial organisation and technical change determine radical changes in the demand for labour, and therefore in wages and income distribution; (5) changes in income distribution and technologies induce changes in consumption behaviour; (6) all above changes depend on how institutions change; (7) last but not least, climate change has heterogeneous impacts on each of

[26] For a well reasoned and concise discussion about the limitations of CGE to model sustainability more in general see Scrieciu (2007).

the above aspects of structural change, which is not predictable without considering how these impacts are distributed. For example, climate change may have an effect on migration through negative impacts on agricultural output. This in turn puts pressure on the political stability of immigration countries, which may further affect investment decisions, the labour market, as well as elections and theretofore climate policies.

Given the restrictive assumptions of IAM, CGE models, most SCM and the aggregate construction of EMK, to date only EABM seem able to take up the challenge of studying the interactions between several aspects of structural change, and with the environment. We have discussed a few examples that have investigated some of these interactions through changes in I/O relations, industrial dynamics, complex and uncertain technical change, technological transitions, employment, income distribution, demand preferences, heterogeneous feedbacks through sectoral shocks, and social interactions.

However, the EABM that have been developed so far exploit only some of the heterogeneity that is likely to influence climate change. Perhaps with the exception of technical change and industrial dynamics, these models tend to study different aspects of structural change separately. Ciarli et al. (2018) provide an example of how crucial aspects of structural change may be integrated in a unified growth model, but lack any reference on the relation with climate change.

The review could inform the next stage of evolutionary complex models, guiding the integration of aspects of structural change which are well developed in other modelling tradition, and in micro evolutionary models, in macro EABM. A better understanding of the complex interactions between structural and climate change might increase our ability to assess the relation between economic activity and climate change, improve the reliability of scenario analysis, and help design climate policies.

## References


**Abernathy, William J. and James M. Utterback**, "Patterns of industrial innovation," *Technology Review*, 1978, *80* (7), 40–47.

**Ackerman, Frank, Stephen J. DeCanio, Richard B. Howarth, and Kristen Sheeran**, "Limitations of integrated assessment models of climate change," *Climatic Change*, apr 2009, *95* (3-4), 297–315.

**Aguiar, Mark and Mark Bils**, "Has Consumption Inequality Mirrored Income Inequality?," *American Economic Review*, sep 2015, *105* (9), 2725–2756.

**Antoci, Angelo, Paolo Russu, and Elisa Ticci**, "Environmental externalities and immiserizing structural changes in an economy with heterogeneous agents," *Ecological Economics*, sep 2012, *81*, 80–91.

**Arrow, Kenneth, Bert Bolin, Robert Costanza, Partha Dasgupta, Carl Folke, C.S. Holling, Bengt-Owe Jansson, Simon Levin, Karl-Göran Mäler, Charles Perrings, and David Pimentel**, "Economic growth, carrying capacity, and the environment," *Ecological Economics*, nov 1995, *15* (2), 91–95.

**Arthur, W Brian**, "Complexity Economics: A Different Framework for Economic Thought," Santa Fe Institute Working Paper: 2013-4-2012, Santa Fe Institute 2013.

**Ayres, Robert U.**, "Industrial metabolism: work in progress," in Jeroen C. J. M. van den Bergh and Marjan W. Hofkes, eds., *Theory and Implementation of Economic Models for Sustainable Development*, Springer Netherlands, 1998, pp. 195–228.

_ **and Jeroen C.J.M. van den Bergh**, "A theory of economic growth with material/energy resources and dematerialization: Interaction of three growth mechanisms," *Ecological Economics*, oct 2005, *55* (1), 96–118.

**Balint, T., F. Lamperti, A. Mandel, M. Napoletano, A. Roventini, and A. Sapio**, "Complexity and the Economics of Climate Change: A Survey and a Look Forward," *Ecological Economics*, aug 2017, *138*, 252–265.

**Barker, Terry**, "The transition to sustainability: a comparison of General-Equilibrium and Space-Time-Economics approaches," Tyndall Centre Working Paper 62 November, Tyndall Centre for Climate Change Research, Cambridge 2004.

**Beinhocker, Eric D.**, *The Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics*, Harvard Business Press, 2006.

**Berg, Maxine**, "From imitation to invention: creating commodities in eighteenth-century Britain," *Economic History Review*, 2002, *55* (1), 1–30.

**Bleda, Mercedes and Marco Valente**, "Graded eco-labels: A demand-oriented approach to reduce pollution," *Technological Forecasting and Social Change*, 2009, *76* (4), 512–524.

**Böhringer, Christoph and Andreas Löschel**, "Computable general equilibrium models for sustainability impact assessment: Status quo and prospects," *Ecological Economics*, nov 2006, *60* (1), 49–64.

**Bosetti, Valentina, Carlo Carraro, Emanuele Massetti, Alessandra Sgobbi, and Massimo Tavoni**, "Optimal energy investment and R&D strategies to stabilize atmospheric greenhouse gas concentrations," *Resource and Energy Economics*, may 2009, *31* (2), 123–137.

**Bottazzi, Giulio and Marco Grazzi**, "Wage-size relation and the structure of work-force composition in Italian manufacturing firms," *Cambridge Journal of Economics*, 2010, *34* (4), 649–669.

**Boulanger, Paul-Marie and Thierry Bréchet**, "Models for policy-making in sustainable development: The state of the art and perspectives for research," *Ecological Economics*, nov 2005, *55* (3), 337–350.

**Bowles, Samuel**, "Endogenous Preferences: The Cultural Consequences of Markets and Other Economic Institutions," *Journal of Economic Literature*, mar 1998, *36* (1), 75–111.

**Bretschger, Lucas and Sjak Smulders**, "Sustainability and substitution of exhaustible natural resources," *Journal of Economic Dynamics and Control*, apr 2012, *36* (4), 536–549.

**Brown, Charles and James Medoff**, "The Employer Size–Wage Effect," *Journal of Political Economy*, oct 1989, *97* (5), 1027–1059.

**Brynjolfsson, Erik and Andrew McAfee**, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, New York: W. W. Norton & Company, 2014.

**Buenstorf, Guido and Christian Cordes**, "Can sustainable consumption be learned? A model of cultural evolution," *Ecological Economics*, nov 2008, *67* (4), 646–657.

**Campiglio, Emanuele**, "The structural shift to green services: A two-sector growth model with public capital and open-access resources," *Structural Change and Economic Dynamics*, sep 2014, *30*, 148–161.

**Capros, P, D van Regemorter, Leonidas Paroussos, P Karkatsoulis, C Fragkiadakis, S Tsani, I Charalampidis, and T Revesz**, "GEM-E3 Model Documentation," JRC Technical Reports EUR 26034 EN, IPTS, Seville 2013.

**Cecere, Grazia, Nicoletta Corrocher, Cédric Gossart, and Muge Ozman**, "Lock-in and path dependence: an evolutionary approach to eco-innovations," *Journal of Evolutionary Economics*, oct 2014, *24* (5), 1037–1065.

**Chang, Ha-Joon**, "Institutions and economic development: theory, policy and history," *Journal of Institutional Economics*, 2010, *FirstView*, 1–26.

**Chenery, Hollis B, Moshe Syrquin, Lance Taylor, and L E Westphal**, *Economic Structure and Performance*, Elsevier Science, 1984.

**Ciarli, Tommaso and María Savona**, "De los cambios cuadráticos a los cambios exponenciales: relación entre estructura económica y sostenibilidad," Technical Report, UN-ECLAC, Santiago 2016.

**_, André Lorentz, Marco Valente, and Maria Savona**, "Structural Changes and Growth Regimes," *Journal of Evolutionary Economics*, 2018, *Forthcomin.*

**_, _, Maria Savona, and Marco Valente**, "The effect of consumption and production structure on growth and distribution. A micro to macro model," *Metroeconomica*, 2010, *61* (1), 180–218.

**Cimoli, Mario and Gabriel Porcile**, "Technology, structural change and BOP-constrained growth: a structuralist toolbox," *Cambridge Journal of Economics*, 2013, *38* (1), 215–237.

**Cincotti, Silvano, Marco Raberto, and Andrea Teglio**, "Credit Money and Macroeconomic Instability in the Agent-based Model and Simulator Eurace," *Economics: The Open-Access, Open-Assessment E-Journal*, 2010, *4* (2010-26), 1.

**Cole, H S D, Chris Freeman, Marie Jahoda, and K L R Pavitt, eds**, *Thinking About the Future: A Critique of 'The Limits to growth'*, London and Brighton: Chatto and Windus/Sussex University Press, 1973.

**Consoli, Davide, Giovanni Marin, Alberto Marzucchi, and Francesco Vona**, "Do green jobs differ from non-green jobs in terms of skills and human capital?," *Research Policy*, jun 2016, *45* (5), 1046–1060.

**Costanza, Robert, Lisa Wainger, Carl Folke, and Karl-G. Mäler**, "Modeling Complex Ecological Economic Systems: Toward an Evolutionary, Dynamic Understanding of Human and Nature," *BioScience*, 1993, *43* (8), 545–555.

**Desmarchelier, Benoît and Faïz Gallouj**, "Endogenous growth and environmental policy: are the processes of growth and tertiarization in developed economies reversible?," *Journal of Evolutionary Economics*, aug 2012, *23* (4), 831–860.

**Desmet, Klaus and StephenL. Parente**, "The evolution of markets and the revolution of industry: a unified theory of growth," *Journal of Economic Growth*, 2012, *17* (3), 205–234.

**Dierdorff, Erich C., Jennifer J. Norton, Donald W. Drewes, Christina M. Kroustalis, David Rivkin, and Phil Lewis**, "Greening of the World of Work: Implications for O*NET-SOC and New and Emerging Occupations," Technical Report, National Center for O*NET Development, Raleigh 2009.

**Dosi, Giovanni, Giorgio Fagiolo, and Andrea Roventini**, "Schumpeter Meeting Keynes: A Policy–Friendly Model of Endogenous Growth and Business Cycles," *Journal of Economic Dynamics and Control*, 2010, *34*, 1748–1767.

**Dynan, Karen E., Jonathan Skinner, and Stephen Zeldes**, "Do the Rich Save More?," *Journal of Political Economy*, 2004, *112* (2), 397–444.

**Enkvist, Per-Anker, Tomas Nauclér, and Jerker Rosander**, "A cost curve for grenhouse gas reduction," *McKinsey Quarterly*, 2007, *Mar* (1), 34–45.

**Faber, Albert and Koen Frenken**, "Models in evolutionary economics and environmental policy: Towards an evolutionary environmental economics," *Technological Forecasting and Social Change*, may 2009, *76* (4), 462–470.

**Fagerberg, Jan, Staffan Laestadius, and Ben R. Martin**, "The Triple Challenge for Europe: The Economy, Climate Change, and Governance," *Challenge*, may 2016, *59* (3), 178–204.

**Fagiolo, Giorgio and Andrea Roventini**, "Macroeconomic Policy in DSGE and Agent-Based Models," *Revue de l'OFCE*, nov 2012, *124* (5), 67.

**Farmer, J. Doyne, Cameron Hepburn, Penny Mealy, and Alexander Teytelboym**, "A Third Wave in the Economics of Climate Change," *Environmental and Resource Economics*, oct 2015, *62* (2), 329–357.

**Freeman, Christopher**, "The greening of technology and models of innovation," *Technological Forecasting and Social Change*, sep 1996, *53* (1), 27–39.

**_ , John Clark, and Luc Soete**, *Unemployment and technical innovation: a study of long waves and economic development*, Frances Pinter, 1982.

**Galeano, Eduardo**, *Las venas abiertas de América Latina*, Mexicoo: Siglo Veintiuno Editores, 1980.

**GEA**, *Global Energy Assessment - Toward a Sustainable Future*, Cambridge, New York & Laxenburg: Cambridge University Press & International Institute for Applied Systems Analysis, 2012.

**Gerst, M. D., P. Wang, Andrea Roventini, Giorgio Fagiolo, Giovanni Dosi, Richard B. Howarth, and Mark E. Borsuk**, "Agent-based modeling of climate policy: An introduction to the ENGAGE multi-level model framework," *Environmental Modelling & Software*, jun 2013, *44*, 62–75.

**Gillingham, Kenneth, Richard G. Newell, and William A. Pizer**, "Modeling endogenous technological change for climate policy analysis," *Energy Economics*, nov 2008, *30* (6), 2734–2753.

**Giupponi, Carlo, Mark E. Borsuk, Bert J.M. de Vries, and Klaus Hasselmann**, "Innovative approaches to integrated global change modelling," *Environmental Modelling & Software*, jun 2013, *44*, 1–9.

**Greenstone, Michael and B. Kelsey Jack**, "Envirodevonomics: A Research Agenda for an Emerging Field," *Journal of Economic Literature*, mar 2015, *53* (1), 5–42.

**Greif, Avner**, *Institutions and the path to the modern economy: lessons from medieval trade* Political economy of institutions and decisions, Cambridge University Press, 2006.

**Grübler, Arnulf, Nebojša Nakićenović, and David G Victor**, "Dynamics of energy technologies and global change," *Energy Policy*, may 1999, *27* (5), 247–280.

**Hardt, Lukas and Daniel W. O'Neill**, "Ecological Macroeconomic Models: Assessing Current Developments," *Ecological Economics*, apr 2017, *134*, 198–211.

**Harris, John R and Michael P Todaro**, "Migration, Unemployment and Development: A Two–Sector Analysis," *American Economic Review*, 1970, *60* (1), 126–142.

**Hidalgo, César A., B Klinger, A.-L. Barabási, and R Hausmann**, "The Product Space Conditions the Development of Nations," *Science*, 2007, *317* (5837), 482–487.

**IEA**, "Ensuring Green Growth in a Time of Economic Crisis : The Role of Energy Technology," Report, IEA, Siracusa 2009.

**Jackson, Tim**, *Prosperity Without Growth: Economics for a Finite Planet*, London: Earthscan, 2009.

_ **and Peter A. Victor**, "Does slow growth lead to rising inequality? Some theoretical reflections and numerical simulations," *Ecological Economics*, jan 2016, *121*, 206–219.

_ **, Ben Drake Surrey, Peter Victor, Kurt Kratena, and Mark Sommer Wifo**, "Foundations for an Ecological Macroeconomics : literature review and model development," Technical Report 65 2014.

_ **, Peter Victor, and Syed Ali Asjad Naqvi**, "Towards a Stock-Flow Consistent Ecological Macroeconomics," Technical Report 2016.

**Jacobsson, Staffan and Anna Bergek**, "Innovation system analyses and sustainability transitions: Contributions and suggestions for research," *Environmental Innovation and Societal Transitions*, jun 2011, *1* (1), 41–57.

**Janssen, Marco A. and Bert J.M. de Vries**, "The battle of perspectives: a multi-agent model with adaptive responses to climate change," *Ecological Economics*, jul 1998, *26* (1), 43–65.

— **and Wander Jager**, "Stimulating diffusion of green products," *Journal of Evolutionary Economics*, jul 2002, *12* (3), 283–306.

**Kauffman, Stuart A and Simon Levin**, "Towards a general theory of adaptive walks on rugged landscapes," *Journal of Theoretical Biology*, 1987, *128* (1), 11–45.

**Kemp-Benedict, Eric**, "The inverted pyramid: A neo-Ricardian view on the economyenvironment relationship," *Ecological Economics*, nov 2014, *107*, 230–241.

**Kim, Linsu**, "Building Technological Capability for Industrialization: Analytical Frameworks and Korea's Experience," *Industrial and Corporate Change*, 1999, *8* (1), 111–136.

**Klepper, Steven**, "Industry Life Cycles," *Industrial and Corporte Change*, 1997, *6* (1), 145–182.

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

— **, Fjalar de Haan, Georg Holtz, Klaus Kubeczko, Enayat Moallemi, George Papachristos, and Emile Chappin**, "Modelling Sustainability Transitions: An Assessment of Approaches and Challenges," *Journal of Artificial Societies and Social Simulation*, jan 2018, *21* (1), 8.

— **, Michael Grubb, David Popp, and Ottmar Edenhofer**, "The transition to endogenous technical change in climate-economy models: A technical overview to the innovation modeling comparison project," *Energy Journal*, 2006, *27* (SPEC. ISS. MAR.), 17–55.

— **, Terry Barker, Dennis Anderson, and Haoran Pan**, "Combining energy technology dynamics and macroeconometrics: The E3MG model," *Energy Journal*, 2006, *27*, 113–133.

**Kratena, Kurt, Gerhard Streicher, Umed Temurshoev, Antonio F. Amores, Iñaki Arto, Ignazio Mongelli, Frederik Neuwahl, José M. Rueda-Cantuche, and Valeria Andreoni**, "FIDELIO 1: Fully Interregional Dynamic Econometric Long-term Input-Output Model for the EU27," JRC Scientific and Policy Reports JRC81864, EC - Institute for Prospective Technological Studies, Seville 2013.

**Kuznets, Simon**, "Modern Economic Growth: Findings and Reflections," *The American Economic Review*, 1973, *63* (3), 247–258.

**Lamperti, Francesco, Giovanni Dosi, Mauro Napoletano, Andrea Roventini, Sandro Sapio, Francesco Lamperti, Giovanni Dosi, Mauro Napoletano, Andrea Roventini, and Sandro Sapio**, "Faraway, so close: coupled climate and economic dynamics in an agent-based integrated assessment model," 2017.

**Lavoie, Marc and Wynne Godley**, "Kaleckian Models of Growth in a Coherent Stock-Flow Monetary Framework: A Kaldorian View," *Journal of Post Keynesian Economics*, dec 2001, *24* (2), 277–311.

**Lazonick, William H.**, "Industrial Relations and Technical Change: The Case of the Self-Acting Mule," *Cambridge Journal of Economics*, sep 1979, *3* (3), 231–262.

— , "Employment relations in manufacturing and international competition," in R Floud and D N McCloskey, eds., *The economic history of Britain since 1700*, second ed., Vol. 2, Cambridge University Press, 1994, chapter 1, pp. 90–116.

**Leach, Melissa, Ian Scoones, and Andy Stirling**, *Dynamic Sustainabilities: Technology, Environment, Social Justice*, Earthscan, 2010.

**Ma, Tieju and Yoshiteru Nakamori**, “Modeling technological change in energy systems From optimization to agent-based modeling,” *Energy*, jul 2009, *34* (7), 873–879.

**Maddison, Angus**, *The World Economy: Historical Statistics*, OECD, 2003.

**Malerba, Franco and Luigi Orsenigo**, “Technological Regimes and Sectoral Patterns of Innovative Activities,” *Industrial and Corporate Change*, 1997, *6* (1), 83–118.

**Mandel, Antoine, Carlo Jaeger, Steffen Fürst, Wiebke Lass, Daniel Lincke, Frank Meissner, Federico Pablo-Marti, and Sarah Wolf**, “Agent-based dynamics in disaggregated growth models,” 2010.

**Martinez-Fernandez, Cristina, Carlos Hinojosa, and Gabriela Miranda**, “Green jobs and skills: the local labour market implications of addressing climate change,” working document, CFE/LEED, OECD, Paris 2010.

**Matsuyama, Kiminori**, “Structural Change,” in Steven N Durlauf and Lawrence E Blume, eds., *The New Palgrave Dictionary of Economics*, second edi ed., Basingstoke: Palgrave Macmillan, 2008.

**Mazzucato, Mariana**, “The PC Industry: New Economy or Early Life-Cycle?,” *Review of Economic Dynamics*, 2002, *5* (2), 318–345.

**McCloskey, Deirdre Nansen**, “Science, Bourgeois Dignity, and the Industrial Revolution,” MPRA Paper 22308 jul 2009.

**Mercure, Jean-Francois, Hector Pollitt, Andrea. M. Bassi, Jorge. E Viñuales, and Neil R. Edwards**, “Modelling complex systems of heterogeneous agents to better design sustainability transitions policy,” *Global Environmental Change*, 2016, *37*, 102–115.

**Mokyr, Joel**, *The gifts of Athena: historical origins of the knowledge economy*, Princeton University Press, 2002.

— , “Knowledge, Enlightenment, and the Industrial Revolution: Reflections on The Gifts of Athena,” *History of Science*, jun 2007, *45*, 185–196.

**Monasterolo, Irene and Marco Raberto**, “A Hybrid System Dynamics Agent Based Model to Assess the Role of Green Fiscal and Monetary Policies,” Technical Report mar 2016.

**Nannen, Volker and Jeroen C.J.M. van den Bergh**, “Policy instruments for evolution of bounded rationality: Application to climateenergy problems,” *Technological Forecasting and Social Change*, jan 2010, *77* (1), 76–93.

**Nelson, Richard Robert and Sidney G Winter**, *An Evolutionary Theory of Economic Change*, Cambridge, MA: Harvard University Press, 1982.

**Nordhaus, William D.**, *Efficient use of energy resources*, New Haven, CT: Yale University Press, jan 1979.

— , “An optimal transition path for controlling greenhouse gases,” *Science*, nov 1992, *258* (5086), 1315–9.

— , *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*, Yale University Press, 2013.

**North, Douglass C**, *Understanding the Process of Economic Change*, Princeton NJ: Princeton University Press, 2005.

**Oltra, Vanessa and Maïder Saint Jean**, "Sectoral systems of environmental innovation: An application to the French automotive industry," *Technological Forecasting and Social Change*, may 2009, *76* (4), 567–583.

**O'Neill, Brian C., Xiaolin Ren, Leiwen Jiang, and Michael Dalton**, "The effect of urbanization on energy use in India and China in the iPETS model," *Energy Economics*, dec 2012, *34*, S339–S345.

**Palma, José Gabriel**, "Structuralism," in Amitava Krishna Dutt and Jaime Ros, eds., *International Handbook Of Development Economics*, Vol. 1, Edward Elgar, 2008, pp. 135–143.

**Pan, Haoran**, "Dynamic and endogenous change of inputoutput structure with specific layers of technology," *Structural Change and Economic Dynamics*, jun 2006, *17* (2), 200–223.

**Pasche, Markus**, "Technical progress, structural change, and the environmental Kuznets curve," *Ecological Economics*, sep 2002, *42* (3), 381–389.

**Pindyck, Robert S**, "Climate Change Policy: What Do the Models Tell Us?," *Journal of Economic Literature*, sep 2013, *51* (3), 860–872.

**Ponta, Linda, Marco Raberto, Andrea Teglio, and Silvano Cincotti**, "An Agent-based Stock-flow Consistent Model of the Sustainable Transition in the Energy Sector," *Ecological Economics*, mar 2018, *145*, 274–300.

**Popp, David**, "ENTICE: endogenous technological change in the DICE model of global warming," *Journal of Environmental Economics and Management*, jul 2004, *48* (1), 742–768.

**_ , Richard G. Newell, and Adam B. Jaffe**, "Energy, the Environment, and Technological Change," in "Handbook of the Economics of Innovation," Vol. 2 of *Handbook of the Economics of Innovation*, Elsevier, 2010, chapter 21, pp. 873–937.

**Prebish, Raul**, *The Economic Development of Latin America and its Principal Problems*, United Nations Department of Economics Affairs, Lake Success, N.Y.: United Nations Publications, 1950.

**Rezai, Armon and Sigrid Stagl**, "Ecological macroeconomics: Introduction and review," *Ecological Economics*, 2016, *121*, 181–185.

**_ , Lance Taylor, and Reinhard Mechler**, "Ecological macroeconomics: An application to climate change," *Ecological Economics*, jan 2013, *85*, 69–76.

**Robalino, David A. and Robert J. Lempert**, "Carrots and sticks for new technology: Abating greenhouse gas emissions in a heterogeneous and uncertain world," *Integrated Assessment*, 2000, *1* (1), 1–19.

**Rosenberg, Nathan**, "Science, Invention and Economic Growth," *The Economic Journal*, 1974, *84* (333), 90–108.

**Safarzyńska, Karolina and Jeroen C.J.M. van den Bergh**, "Demand-supply coevolution with multiple increasing returns: Policy analysis for unlocking and system transitions," *Technological Forecasting and Social Change*, feb 2010, *77* (2), 297–317.

**_ and _** , "Evolving power and environmental policy: Explaining institutional change with group selection," *Ecological Economics*, feb 2010, *69* (4), 743–752.

— , **Koen Frenken, and Jeroen C.J.M. van den Bergh**, "Evolutionary theorizing and modeling of sustainability transitions," *Research Policy*, jul 2012, *41* (6), 1011–1024.

**Sassi, Olivier, Renaud Crassous, Jean-Charles Hourcade, Vincent Gitz, Henri Waisman, and Celine Guivarch**, "IMACLIM-R: a modelling framework to simulate sustainable development pathways," *International Journal of Global Environmental Issues*, mar 2010, *10* (1/2), 5–24.

**Saviotti, Pier Paolo and Jean Luc Gaffard**, "Preface for the special issue of JEE on 'Innovation, structural change and economic development'," *Journal of Evolutionary Economics*, 2008, *18* (2), 115–117.

**Savona, Maria and Tommaso Ciarli**, "Structural Changes and Climate Change. A Selected Review of the Empirical Stylised Facts," 2017.

**Scrieciu, S. Serban**, "The inherent dangers of using computable general equilibrium models as a single integrated modelling framework for sustainability impact assessment. A critical note on Böhringer and Löschel (2006)," *Ecological Economics*, feb 2007, *60* (4), 678–684.

— , **Armon Rezai, and R. Mechler**, "On the economic foundations of green growth discourses: the case of climate change mitigation and macroeconomic dynamics in economic modeling," *Wiley Interdisciplinary Reviews: Energy and Environment*, may 2013, *2* (3), 251–268.

**Silverberg, Gerald and Bart Verspagen**, "A percolation model of innovation in complex technology spaces," *Journal of Economic Dynamics and Control*, 2005, *29* (1-2), 225–244.

— **and** — , "The size distribution of innovations revisited: An application of extreme value statistics to citation and value measures of patent significance," *Journal of Econometrics*, aug 2007, *139* (2), 318–339.

**Singer, H K**, "The Distribution of Gains Between Investing and Borrowing Countries," *American Economic Review*, 1950, *40*, 473–485.

**Smith, Adam**, *An Inquiry into the Nature and Causes of the Wealth of Nations*, edwin cann ed., London: Methuen, 1961.

**Smith, Adrian, Andy Stirling, and Frans Berkhout**, "The governance of sustainable socio-technical transitions," *Research Policy*, dec 2005, *34* (10), 1491–1510.

**Stapleton, Lee, Steve Sorrell, and Tim Schwanen**, "Estimating Direct Rebound Effects for Personal Automotive Travel in Great Britain," *SPRU Working Paper Series*, 2015, (08).

**Stern, Nicholas**, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, 2007.

— , "The Economics of Climate Change," *American Economic Review*, apr 2008, *98* (2), 1–37.

— , "The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models," *Journal of Economic Literature*, sep 2013, *51* (3), 838–859.

— , "Economics: Current climate models are grossly misleading," *Nature*, feb 2016, *530* (7591), 407–409.

**Steve Sorrell**, "The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency," UK Energy Research Centre, UERC 2007.

**Stirling, Andy**, "Direction, Distribution and Diversity! Pluralising Progress in Innovation, Sustainability and Development," STEPS Working Paper 32, STEPS Centre, Brighton 2009.

**Teglio, Andrea, Andrea Mazzocchetti, Linda Ponta, Marco Raberto, and Silvano Cincotti**, "Budgetary rigour with stimulus in lean times: Policy advices from an agent-based model," *Journal of Economic Behavior & Organization*, oct 2017.

**Tesfatsion, L and K L Judd, eds**, *Agent-Based Computational Economics: A Constructive Approach to Economic Theory*, Vol. 2 of *Handbook of Computational Economics*, Elsevier, 2006.

**van den Bergh, Jeroen C.J.M.**, "Environmental and climate innovation: Limitations, policies and prices," *Technological Forecasting and Social Change*, jan 2013, *80* (1), 11–23.

_ **and John M. Gowdy**, "Evolutionary Theories in Environmental and Resource Economics: Approaches and Applications," *Environmental and Resource Economics*, 2000, *17* (1), 37–57.

_ **, Bernhard Truffer, and Giorgos Kallis**, "Environmental innovation and societal transitions: Introduction and overview," *Environmental Innovation and Societal Transitions*, jun 2011, *1* (1), 1–23.

**van der Meijden, Gerard and Sjak Smulders**, "Technological Change During the Energy Transition," *Macroeconomic Dynamics*, jun 2018, *22* (04), 805–836.

**van der Ploeg, Frederick**, "Macroeconomics of sustainability transitions: Second-best climate policy, Green Paradox, and renewables subsidies," *Environmental Innovation and Societal Transitions*, jun 2011, *1* (1), 130–134.

_ **and Cees Withagen**, "Is there really a green paradox?," *Journal of Environmental Economics and Management*, nov 2012, *64* (3), 342–363.

**van Ruijven, Bas, Frauke Urban, René M.J. Benders, Henri C. Moll, Jeroen P. van der Sluijs, Bert J.M. de Vries, and Detlef P. van Vuuren**, "Modeling Energy and Development: An Evaluation of Models and Concepts," *World Development*, dec 2008, *36* (12), 2801–2821.

**Vergara, Walter, Ana R. Rios, Luis Miguel Galindo Paliza, Pablo Gutman, Paul Isbell, Paul H. Suding, and Joseluis Samaniego**, *The Climate and Development Challenge for Latin America and the Caribbean. Options for Climate-Resilient, Low-Carbon Development*, Washington DC: Inter-American Development Bank, apr 2013.

**von Tunzelmann, G Nick**, *Technology and Industrial Progress: The Foundations of Economic Growth*, Aldershot: Edward Elgar, 1995.

**Vona, Francesco and Davide Consoli**, "Innovation and skill dynamics: a life-cycle approach," *Industrial and Corporate Change*, oct 2014, pp. dtu028–.

_ **and Fabrizio Patriarca**, "Income inequality and the development of environmental technologies," *Ecological Economics*, sep 2011, *70* (11), 2201–2213.

**Wei, Yi-Ming, Zhi-Fu Mi, and Zhimin Huang**, "Climate policy modeling: An online SCI-E and SSCI based literature review," *Omega*, dec 2015, *57* (A), 70–84.

**Weitzman, Martin L.**, "On Modeling and Interpreting the Economics of Catastrophic Climate Change," *Review of Economics and Statistics*, feb 2009, *91* (1), 1–19.

_ , "Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change," *Review of Environmental Economics and Policy*, aug 2011, *5* (2), 275–292.

— , “Fat Tails and the Social Cost of Carbon,” *American Economic Review*, may 2014, *104* (5), 544–546.

**Windrum, Paul, Tommaso Ciarli, and Chris Birchenhall**, “Consumer heterogeneity and the development of environmentally friendly technologies,” *Technological Forecasting and Social Change*, 2009, *76* (4), 533–551.

**— , — , and —** , “Environmental impact, quality, and price: Consumer trade-offs and the development of environmentally friendly technologies,” *Technological Forecasting and Social Change*, 2009, *76* (4), 552–566.

**Witt, Ulrich**, “Learning to Consume - A Theory of Wants and the Growth of Demand,” *Journal of Evolutionary Economics*, 2001, *11*, 23–36.

— , “The dynamics of consumer behavior and the transition to sustainable consumption patterns,” *Environmental Innovation and Societal Transitions*, jun 2011, *1* (1), 109–114.

**Wolf, Sarah, Franziska Schütze, and Carlo Jaeger**, “Balance or Synergies between Environment and EconomyA Note on Model Structures,” *Sustainability*, aug 2016, *8* (8), 761.

**— , Steffen Fürst, Antoine Mandel, Wiebke Lass, Daniel Lincke, Federico Pablo-Martí, and Carlo C. Jaeger**, “A multi-agent model of several economic regions,” *Environmental Modelling & Software*, jun 2013, *44*, 25–43.

**Zeppini, Paolo and Jeroen C.J.M. van den Bergh**, “Competing Recombinant Technologies for Environmental Innovation: Extending Arthur’s Model of Lock-In,” *Industry & Innovation*, apr 2011, *18* (3), 317–334.

# A Tables

| | | Aspects of structural change | | | |
|---|---|---|---|---|---|
| Sectors | IO | Technical change | Employment | Demand | Institutions |
| Contribution to GHG | New intermediate sectors | Factor bias | Green jobs | Income distribution | Appropriation regimes |
| Innovative activity | I/O coefficients | Clean energy | Unemployment | Consumption preferences | Tech opportunities |
| Cost of abatement | Firm size | Radical innovations / trajectories | Distribution of wages | Time preferences | Access to resources |
| I/O relations | Industrial dynamics | Non linear and clustered process | Labour intensity | | Governance |
| Dematerialisation | Geographic concentration | Uncertainties & unintended effects | Labour composition | | Social interactions |

*Notes*: We consider that a specific model considers one aspect of structural change if any of the listed changes is endogenous to the model (e.g. if a model has a fixed I/O structure, and none of the other aspects changes, we do not consider that it embeds features of structural change).

Table 1: ***Aspects of structural change: main components interacting with climate change***

| Models | Aspects of structural change | | | | | |
|---|---|---|---|---|---|---|
| | **Sectors** | **IO** | **Technical change** | **Employment** | **Demand** | **Institutions** |
| IAM | No: Aggregate & exogenous – no sectoral changes | No | Partial: Exogenous, LBD, induced TC, but aggregate | No | Limited: time preferences change with pollution | No (Policy experiments) |
| CGE | Partial: many sectors, with technical change that may affect GHG | No: I/O maps diversification, but static | Partial: Semi-exogenous, LBD, induced TC, but aggregate | No | Limited: change consumption patterns, not preferences | No (Policy experiments) |
| SCM | Yes | Yes, but only a couple of models | Yes, but only a couple of models | No | Limited: two populations | No (Policy experiments) |
| EMK | Partial: labour composition | Not yet | No | Yes | Limited: wage distribution | No (Policy experiments) |
| EABM 1 | Partial: weaker on the environmental effects | Limited: firm size & industrial dynamics | Largely Yes | Yes | Yes, although not developed | Partial: interaction & response to policies |
| EABM 2 | No | Limited: mainly industrial dynamics | Yes | No | Yes | Partial: Evolution of power and tech. opportunities |

Notes: IAM: integrated assessment models; CGE: computable general equilibrium models; SCM: structural change models; EMK: ecological macroeconomics (Keynesian); EABM 1: evolutionary and multi agent models (macro); EABM 2: evolutionary and multi agent models (innovations)

Table 2: ***Aspects of structural change in different modelling traditions.*** *Some models are better equipped than others to capture the relation between aspects of structural change and environmental impact. In particular those that do not require a closed form solution in equilibrium.*

| Aspects of structural change | Models | | | | |
|---|---|---|---|---|---|
| | **IAM** | **CGE** | **SCM** | **EMK** | **EABM** |
| **Sectors** | | | | | |
| Contribution to GHG | | ✓ | ✓ | ✓ | ✓ |
| Innovative activity | | ✓ | ✓ | | ✓ |
| Cost of abatement | | | | | |
| I/O relations | | ✓$^{\dagger}$ | ✓ | | ✓ |
| Dematerialisation | | | ✓ | | |
| **IO** | | | | | |
| New intermediate sectors | | | ✓ | | |
| I/O coefficients | | | ✓ | ✓$^{*}$ | ✓ |
| Firm size | | | | | ✓ |
| Geographic concentration | | | | | |
| Industrial dynamics | | | | | ✓ |
| **Technical change** | | | | | |
| Factor saving | ✓ | ✓ | ✓ | | ✓ |
| Clean energy | ✓ | ✓ | ✓ | | ✓ |
| Radical innovations/trajectories | | | ✓ | | ✓ |
| Non linear and clustered process | | | | | ✓ |
| Uncertainties & undesired effects | | | | | ✓ |
| **Employment** | | | | | |
| Green jobs | | | | | ✓ |
| Unemployment | | | | ✓ | ✓ |
| Distribution of wages | | | | ✓$^{*}$ | ✓ |
| Labour intensity | | | | ✓$^{*}$ | ✓ |
| Labour composition | | | ✓ | ✓ | |
| **Demand** | | | | | |
| Income distribution | | | ✓ | ✓$^{*}$ | ✓ |
| Consumption preferences | | ✓$^{1}$ | | | ✓ |
| Time preferences | ✓ | | | | |
| **Institutions** | | | | | |
| Appropriation regimes | | | | | |
| Tech opportunities | | | | | ✓ |
| Access to resources | | | | | |
| Governance | | | | | ✓ |
| Social interactions | | | | | ✓ |

*Notes*: The table provides a bird's-eye view of which components of the six aspects of structural change considered in the paper. It should also be noted that models differ substantially (especially moving from SCM to the right): for a more specific discussion of some of the models the reader should refer to the relevant parts in Section 3. IAM: integrated assessment models; CGE: computable general equilibrium models; SCM: structural change models; EMK: ecological macroeconomics (Keynesian); EABM: evolutionary multi agent models (including micro models).

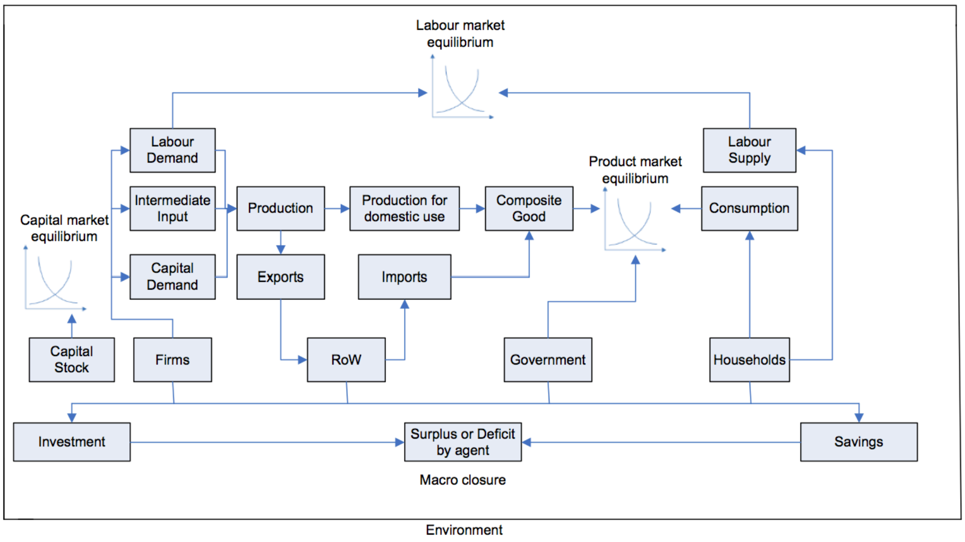
$^{*}$ indicates that the change is to be included in forthcoming models

$^{\dagger}$ learning by doing

$^{1}$ changes in consumption patterns rather than preferences

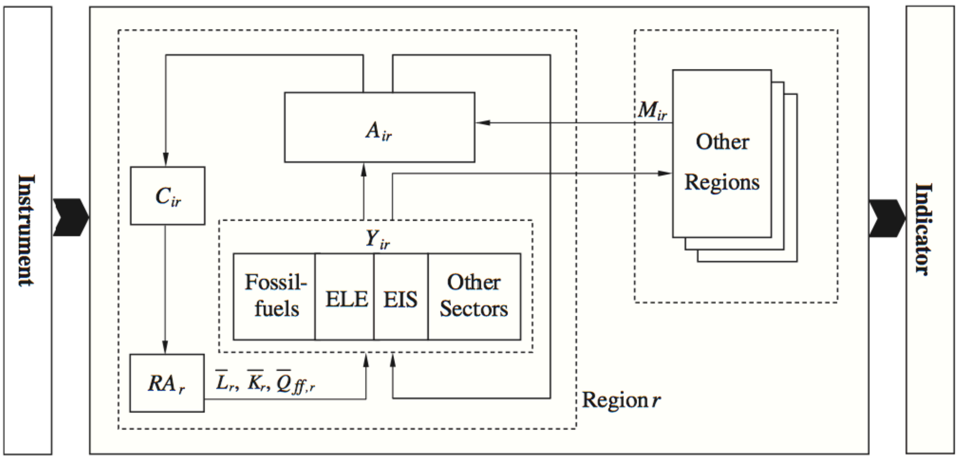
Table 3: ***Components of structural change in different modelling traditions.***

# B Figures



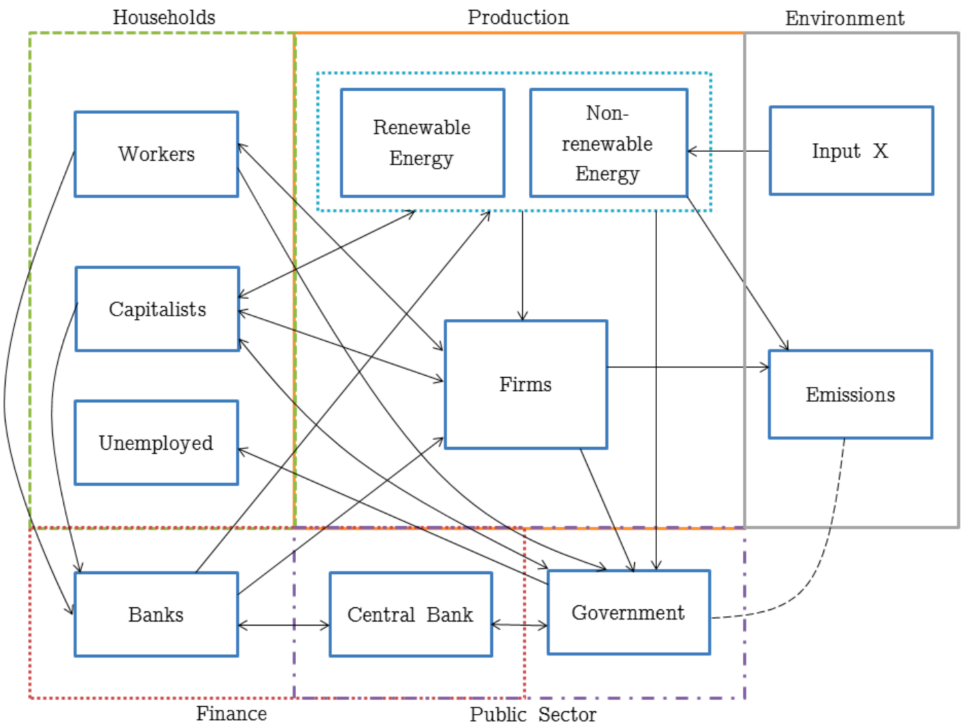

***Notes***. Source: Capros et al. (2013)

Figure 1: ***The economic components and markets of a CGE model***.




***Notes***. $Y_i$ is output of commodity $i$, using energy and non energy inputs; $L$, $K$, and $Q$ are, respectively, labour, capital and fossil fuels inputs; output may be fossil fuels, electricity (ELE), energy intensive sectors (EIS) and other sectors; $C_i$ is consumption of the representative agent $RA$ of commodity $i$; $A_i$ are all domestic final and intermediate goods; and $M_i$ are all imported final and intermediate goods. Source: Böhringer and Löschel (2006)

Figure 2: ***Basic CGE structure***




***Notes***. Source: Jackson et al. (2016)

Figure 3: ***Overall structure of a rich EMK model: ECOGRO***

# Recent papers in the SPRU Working Paper Series:

**December**

*Diffusion of Shared Goods in Consumer Coalitions. An Agent-Based Model.* Francesco Pasimeni and Tommaso Ciarli.

**November**

*How Deep Is Incumbency? Introducing a 'Configuring Fields' Approach to the Distribution and Orientation of Power in Socio-Material Change.* Andy Stirling.

*Scientific Output of US and European Universities Scales Super-Linearly with Resources.* Benedetto Lepori, Aldo Geuna and Antonietta Mira.

*Do Firms Publish? A Multi-Sectoral Analysis.* Roberto Camerani, Daniele Rotolo and Nicola Grassano.

**October**

*A Co-Evolutionary, Long-Term, Macro-Economic Forecast for the UK Using Demographic Projections.* Nick Jagger.

*How Can Intermediaries Promote Business Model Innovation: The Case of 'Energiesprong' Whole-House Retrofits in the United Kingdom.* Donal Brown, Paula Kivimaa and Steven Sorrell.

*Climate Resilience Pathways of Rural Households. Evidence from Ethiopia.* Solomon Asfaw, Giuseppe Maggio and Alessandro Palma.

*Public Procurement and Reputation: An Agent-Based Model.* Nadia Fiorino, Emma Galli, Ilde Rizzo and Marco Valente.

**Suggested citation:**
Tommaso Ciarli and Maria Savona (2019). Modelling the Evolution of Economic Structures and Climate Changes: A Review. SPRU Working Paper Series (SWPS), 2019-01: 1-41. ISSN 2057-6668. Available at: www.sussex.ac.uk/spru/swps2019-01

Science Policy Research Unit
University of Sussex, Falmer
Brighton BN1 9SL
United Kingdom

SPRU website: **www.sussex.ac.uk/business-school/spru**
SWPS website: **www.sussex.ac.uk/business-school/spru/research/swps**
Twitter: **@spru**

UNIVERSITY OF SUSSEX | BUSINESS SCHOOL