# Emergence of new economics energy transition models: a review

# Abstract

Well-known academic and non-academic institutions call for a new approach in economics able to capture features of modern economies including, but not limited to, complexity, non-equilibrium and uncertainty. In this paper, we provide a systematic review of ecological macroeconomic models that are suitable for the investigation of low-carbon energy transitions and assess them based on the features considered desirable for a new approach in economics. We draw two main conclusions: firstly, the knowledge base and structure of these existing ecological macroeconomic models are relevant, alongside other types of models, for the creation of a new approach in economics. Secondly, the reviewed models are policy relevant, especially in the context of the complexity and urgency of rapid energy transitions, where increasingly policymakers require economic models able to capture real-world characteristics. However, further improvements are needed to these models and future research should focus on i) assuring comparability of models’ results and their policy insights, ii) incorporation of the relationships between macroeconomics, finance and sustainability and iii) the institutionalization of a new approach in economics.

**Keywords**: Rebuilding macroeconomics; New approaches in economics; Ecological macroeconomic models; Energy-economic models; Low-carbon energy transition

# 1. Introduction

Until the Great Financial Crisis (GFC) in 2008, most neoclassical economists were confident about the ability of their macroeconomic models, which include Dynamic Stochastic General Equilibrium (DGSE) or Computational General Equilibrium (CGE) models, to represent and understand the main macroeconomic mechanisms (Blanchard, 2009; Stiglitz, 2018). Using the above mentioned modelling approaches these economists also believed that the main challenges of the real economy, i.e. economic instability and crises, could be considered as solved (e.g. Blanchard, 2009; Lucas, 2003, Christiano et al. 2018).

However, the GFC challenged this belief and put economists under pressure from academic and non-academic experts. The inability of mainstream economics models to foresee the financial crisis was considered by several economists as a ‘problem of imagination’ (Posner 2009), or as ‘wishful thinking and hubris’ (Giles, 2009). The GFC highlighted some of the major challenges behind mainstream approaches, and in particular the consequences of their shortcoming to represent the ‘bigger picture’, i.e. the way society, politics, economics and finance constitute an organic whole, where everything has consequences in the short and long term (Stiglitz, 2018; Keen, 2011). Various authors from different schools of economic thought highlight limitations and deficiencies of current macroeconomic models (e.g. Colander et al., 2009; Kirman, 2010; Haldane & Turrell, 2018; Stiglitz, 2018; Blanchard, 2018; Lavoie, 2014; Barker, 2011). In particular, Colander et al. (2009) claim that these models ‘by design, disregard key elements driving outcomes in real-world markets’ and Haldane & Turrell (2018) and Kirman (2010) call for new approaches in economics to overcome the over-simplifying assumptions in CGE/DSGE models, such as the assumption of representative agents, rationality and optimising behaviour.

This call for a new economics approach has emerged from both academic (e.g. Haldane & Turrell, 2018; McKibbin & Stoeckel[[1]](#footnote-1)) and non-academic institutions (e.g. OECD, 2017; Institute of New Economics Thinking (INET[[2]](#footnote-2))). The various proponents of a new approach emphasise the importance of multidisciplinary approaches to economics, both in terms of methods and research areas involved, and call for development of analytical tools that capture features such as complexity, radical or deep uncertainty (Knight, 1921), non-ergodicity, discontinuities, tipping points, path-dependency and feedback loops. According to these calls, new economics modelling should apply a systems-perspective and be capable of evaluating multidimensional policy objectives, such as well-being alongside GDP, environmental sustainability and distributional issues (OECD, 2015; OECD, 2017).

Despite the above, economic models with a neoclassical theoretical underpinning are still widely applied for macroeconomic and climate policy analysis (Scrieciu, 2007; Scrieciu et al., 2013; Ackerman, 2014; Haldane & Turrell, 2018). However, the consideration of complexity, out-of-equilibrium and other features of real-world economies is crucial for meaningful policy intervention as policy assessment is otherwise biased and policy intervention likely leads to sub-optimal policy outcomes (e.g. Mercure et al., 2019). Therefore, it is important to investigate whether there already exist non-equilibrium models that can be applied to concrete policy questions overcoming (some of) the shortcomings of economic models, based on a neoclassical framework[[3]](#footnote-3). For example, the OECD as well as Rebuilding Macroeconomics discuss non-equilibrium modelling approaches (e.g. stock-flow-consistent modelling or agent-based modelling) for a new approach in economics[[4]](#footnote-4).

We provide a systematic review of existing non-optimization ecological macro-economic models applicable for policy evaluation of the low-carbon energy transition In the context of the complexities of rapid decarbonisation of energy systems, decision makers are in need of economic models, able to capture out-of-equilibrium dynamics, complexity and other features of a new approach in economics (see Doukas et al., 2018). We focus on energy transition models on one hand due to their relevance in the debate on post-growth economics (Victor, 2012; Ayres & Warr, 2010; Victor & Jackson, 2019). On the other hand, because of the currently high political relevance of energy transitions in the context of the urgently required political action to maintain global temperature below the two-degree target (e.g. EC, 2014; UN, 2018). Identified ecological economics energy transition models are compared against their ability to consider the desired features of a new economic approach (e.g. OECD, 2015; 2017), including: i) complexity, non-linearity, non-ergodicity and deep uncertainty), (ii) the importance of time, (iii) agents’ heterogeneity and behavioural elements, (iv) interdisciplinary aspects (v) role of institutions and social context, (vi) ethical and philosophical aspects, (vii) finance and viii) multiple equilibria/disequilibrium.

We address two questions:

1. What ecological macroeconomics models, applicable to evaluate climate policies for the low-carbon energy transition, fulfil, at least to some degree, the desired characteristics i) to viii) (see above) of a new economic approach?
2. How do current ecological economics models, applicable to the energy transition, account for the desired characteristics i) to viii) (see above)?

The first question is addressed through a literature review, while the second is addressed by a model-review based on the literature and by interviewing leading researchers working with those models. Our review aims to help policymakers and non-modellers to understand the structural underpinning of the models they use. It also serves as an information repository on the structure of the reviewed models, and as a knowledge basis for further model advancements of energy transition models and rebuilding macroeconomics. We are not aware of any previous study that has reviewed current energy transition models in the ecological macroeconomics literature based on the features characterising a new approach in economics and our paper is thus complementary to the recent systematic ecological macroeconomic model review by Hardt & O’Neill (2017)[[5]](#footnote-5).

The paper is organized as follows. Section 2 gives an overview why a new approach in economics is useful and introduces the desirable characteristics of this new approach. Section 3 describes the evaluation-framework for the model review and the applied information collection process. Section 4 gives a summary of different simulation modelling approaches and the identified models, and discusses the results highlighting similarities and differences of the models, as well as their strengths and weaknesses. Section 5 concludes.

# 2. Call for a new economic approach

Computational General Equilibrium (CGE) models are among the most often used policy tools for the assessment of economic and climate policies (e.g. Scrieciu et al., 2013; Ackerman, 2014). These models are based on the economic theoretical underpinning of General Equilibrium Theory and neoclassical economics, or in other words ‘CGE models are the quantitative expressions of the marginal analysis of mainstream neoclassical economics’ (Barker, 2004, p.4). More specifically, CGE modelling is grounded on economic theory going back to Walras (1874) and Arrow & Debreu (1954). This economic theory imposes a set of assumptions on CGE models including but not limited to rationality, the assumption of representative agents and firms, the assumptions of constant returns to scale and the assumption of cleared markets in the long-run (Dixon & Jorgenson, 2013; DeCanio, 2003). The first CGE model built was in the 1960s by Johansen (Johansen, 1960). Current examples include GEM-E3 (Capros et al, 2013) or GTAP Model (Hertel, 1999), which are well-known international CGE models applied in the area of climate and energy economics.

Dynamic Stochastic General Equilibrium (DSGE) models are often described as the follower of business cycle models and generally applied by central banks for economic policy analysis. Thereby, these models are said to be ‘dynamic’ as they account for time (i.e. they distinguish between short- and long-term), they are ‘stochastic’ as they include close to equilibrium stochastic shocks in their simulations, they are ‘general’ as they describe the entire economy and they are ‘equilibrium’ models as they follow the Walras and Arrow-Debreu tradition, although they also include some non-Walrasian features (e.g. sticky prices, frictions in financial markets) (Christiano & Eichenbaum, 2018; Galí, 2015). However, DSGE models are generally characterized by the same problematic assumptions as CGE models, including rational expectations, representative agents or perfect markets and do generally not include a financial sector (Fagiolo & Roventini, 2016; Stiglitz, 2018). Importantly, although DSGE models sometimes introduce additional variables (e.g. searching costs for information) to account for deep uncertainty, bounded rationality or imperfect information, they nevertheless assume optimising agents and convergence towards a (long-term) equilibrium. Relatedly, the stochastic elements of DSGE-model do not account for the concept of deep-uncertainty (Keen, 2011; Gowdy & Erickson, 2005).

Advantages and disadvantages of neoclassical theory and CGE/DSGE modelling are well discussed in the research-literature (e.g. Ackerman, 2002; Kirman, 1989; 1992; Stiglitz, 2018; Haldane & Turrell, 2018; Christiano et al., 2018; Fagiolo & Roventini, 2016). These studies have demonstrated that the assumptions, including for example rationality, representative agents and market equilibrium in the long-term, of neoclassical theory are flawed. There are other studies pointing towards the limitations of the ontology and epistemology[[6]](#footnote-6) in neoclassical theory (e.g. Spash, 2012; Dow, 1997). In spite of the above, it is still common practice among policymakers to apply CGE models for the evaluation of climate policy (Wing, 2007; 2011; Scrieciu, 2007; Ackerman, 2014)[[7]](#footnote-7). The fact that in the latest IPCC-report includes thirty out of thirty-one models are GCE or DSGE models illustrates this well (IPCC, 2014).

The call for a new economic approach is not new and goes back to 1920’s (Scrieciu, 2011). An increasing amount of research literature emphasises the need for economic models to capture real-world characteristics such as complexity, feedback loops, path-dependency, uncertainty and multiple heterogeneous interacting agents (e.g. Barker, 2004; Foxon, 2013; Mercure et al., 2016). This strand of research literature underlines that models for the simulation of long-term transitions, such as low-carbon energy transitions, should account for these above-mentioned features and be able to represent system-changes in their full complexity rather than only marginal changes as proposed in the neoclassical tradition (Holtz et al., 2015; Rezai & Stagl, 2016; Wolf et al., 2016).

The call for new approaches in economics’ (e.g. OECD, 2015; 2017; Barker, 2008; 2011; INET, 2019; Haldane & Turrell, 2018), include the following key characteristics/features:

1. **Complexity, non-linearity, non-ergodicity[[8]](#footnote-8) and deep uncertainty**: The economy is a complex, interconnected and non-linear system characterized by deep uncertainty (Knight, 1921).
2. **Importance of time, path-dependency, lock-in and irreversibility**: The initial conditions of the economy have an impact on the simulation outcome. For example, technological change includes path-dependency and lock-in due to learning effects and firms cannot change their production technology immediately (e.g. due to earlier investments). The importance of time and irreversibility includes nature and its services (ecosystem services) that cannot be converted into money and back again.
3. **Agents’ heterogeneity and behavioural elements:** includes the representation of heterogeneous agents and interactions among these individual agents are based on varying behavioural insights (e.g. heuristics) rather than on the assumption of rationality. It includes evaluation of policy impacts on different agent-classes (e.g. differentiated by income categories).
4. **Interdisciplinary:** respecting insights and knowledge from other disciplines (e.g. psychology, ethics, history and engineering as well as complexity and evolutionary theory).
5. **Role of institutions and social context:** based on the economic history of institutional structures, institutional inertia and emphasises the impact of social context, history of agents, institutional structures and power relationships on the behaviour of agents and the overall economy.
6. **Ethical and moral philosophical aspects:** acknowledging that economics is not value-free and should therefore also be informed by ethical philosophy.
7. **Finance:** including the simulation of monetary flows explicitly. In particular, macroeconomic models should track all monetary flows (e.g. income or expenditures) and assure that the model overall is stock-flow consistent (i.e. Someone’s asset is someone else’s liability and someone’s inflow is someone else’s outflows and no fund can come from (or end up) nowhere).
8. **Multiple equilibria/disequilibrium:** the economy is described as an evolving and adaptive system that is interconnected, complex and characterized by multiple equilibria or disequilibrium.

That is, according to various economic schools of thought new modelling approaches should be capable of capturing path-dependency, non-linearity/threshold-levels, heterogeneity of agents, deep uncertainty, interconnections between agents, multiple equilibria and feedback-loops. The importance of institutions, political economies and long-term perspectives should be included. The call also emphasizes the linkages of the economy with the environment and the financial system and the consideration of multi-dimensional policy objectives (e.g. multi-dimensional well-being).

These features are particularly relevant in the case of a low-carbon energy transition. The decarbonisation of the energy system is a complex out-of-equilibrium transition, characterised by long-term structural changes and interactions of various agents without perfect foresight. Recent research demonstrates that a transition towards a low-carbon energy system requires the understanding of behavioural aspects. Li & Strachan (2017) highlights the existence of various political (e.g. willingness to pay higher electricity prices) and social (e.g. openness or reluctance towards new technologies) barriers, thus contrasting the commonly adopted view that rational actors are characterised by purely cost optimising behaviour (Mignon & Bergek, 2016). Hafner et al. (2019; 2020) show the relevance of behavioural (e.g. biased risk perceptions) and other green investment barriers (e.g. policy uncertainty) in the context of the ‘green finance’ gap, which describes the lack of investments into renewable energy infrastructure capacity. Importantly, a lack of an adequate representation of behavioural factors in energy-economics models might lead to the misleading conclusion that pricing policies (e.g. carbon price) are the most effective way to change actor behaviour. However, when behavioural aspects are relevant regulatory changes, technology (e.g. R&D subsidies) or sectoral policies can play a relevant part too (Mercure et al., 2019). Finally, the representation of heterogeneous actors (e.g. differentiated according to income or skills) are for example relevant for the evaluation of distributional effects of policies designed to decarbonise the energy sector (Markkanen & Anger-Kraavi, 2019; Jenkins et al., 2016).

The representation of non-equilibrium and dis-equilibria states is important for model outcomes and policy design in the context of low-carbon transitions. The convergence towards an (optimal) equilibrium is generally based on the assumption of rational actors that take optimal decisions on the grounds of having access to (near-)perfect information and the capacity to proceed all available information. This has the implication that the base-run can said to be ‘normative’ and thus likely to be over-optimistic as it is based on the assumption that agents perform in an optimal way. This means that the calculated ‘costs’ of policies introduced in an ‘optimal base-run’ are higher as compared to a more ‘realistic’ base-run in which agents are influenced by behavioural aspects and do not have access to near-perfect information (Mercure et al., 2019; Pollitt, 2019). Second, the convergence towards an equilibrium is further based on the assumptions that agents react only to price changes and that there exist only one government agent. However, besides the importance of behavioural aspects, mentioned above, research from the sustainability-transition literature (Markard et al., 2012) demonstrates the importance of political, organizational, cultural and social changes, institutions, governance and the coordination policies, of forward-planning and information-exchange among different decisions makers (Bolton & Foxon, 2015a; b; Van den Bergh et al., 2011). This in turn implies that the impact of policies are over-estimated in equilibrium models when in reality additional behavioural impacts, lock-in, path-dependencies and the interactions among various decision-makers on regional, national and international levels and across various sectors determine policy outcomes in addition (Mercure et al., 2019; Li & Strachan, 2017). Finally, the convergence towards an equilibrium assumes that agents undertake marginal change in their consumption, however, the transitions towards a low-carbon energy supply sector, implies deep systemic changes, involving for example changes in key technologies used to produce energy or the way current energy consumption and production are organised (e.g. decentralised energy production) (Bolton & Foxon, 2015a; b). This means that is important for energy-transition models that they are suitable, at least to some extent, to simulate these system-wide non-marginal changes.

Finally, the representation and consideration of finance matters in the evaluation of climate policies designed to decarbonize current energy systems. For example, Mercure et al. (2019) demonstrate the theory of finance (i.e. adoption of endogenous vs. exogenous money supply) drives whether or not the GDP effects of climate policies are positive or negative. That is, the representation of finance and money has implications on model outcomes and policy implications, in particular in the context of an energy transition that requires a large amount of investments to build new renewable energy capacity.

# 3. Methodology

*3.1. Model selection*

We reviewed all published models (to the best of our knowledge) within the field of ecological macroeconomics or related fields that are able to simulate the low-carbon transition of the energy supply sector.

These models are characterised by the following criteria:

1. inclusion of an energy supply sector that simulates at least two energy supply technologies explicitly;
2. inclusion of at least two sectors[[9]](#footnote-9) of a typical macroeconomic model;
3. Peer-reviewed scientific literature, working paper or policy report that summarises the results of the evaluation of policies/scenarios that deliver the required reduction of emissions in the energy supply industry necessary to reach the temperature targets of the Paris Agreement;
4. documented in peer-reviewed scientific literature, working papers or policy reports, and written in English language.

We started with including all models that satisfy the above explained requirements, from the recent review of Hardt & O’Neill (2017). This review includes existing models within the ecological economics literature but is limited to models that describe the total monetary economy in mathematical terms. Building on this study, our analysis considers additional models found in the academic literature related to ecological macroeconomics[[10]](#footnote-10). Similar to the review of Hardt & O’Neill (2017) our review excludes models based on General Equilibrium theory and neoclassical economics.

The information sources on the modelling-structure of the identified models are from i) a literature review, and ii) if we did not find relevant information in published journals, policy reports or working papers, we used conference presentations or semi-structured interviews which were conducted with the researchers developing the models in person, or via e-mail or skype.

*3.2. Model review process and evaluation*

The objective of our model review was to evaluate how the identified models account for the desired features i) to viii) of a new economic approach.

We first documented the structure of the identified models along a set of different model cores, including the following: A) Economic structure, B) Technology treatment, C) Treatment of agents’ behaviour and time, D) Appearance of government and central bank, E) Energy supply sector and F) Integration of the environment. Most of these cores include a set of subtopics (see table 1). The introduction of subtopics allows a more detailed discussion on how the reviewed models account or do not account for the different desired features i) to viii) of a new approach in economics. For all reviewed models, the complete documentation of cores A) to F), including the indicated subtopics, can be found in the supplementary material. For further information, our model documentation contains in addition information energy transition policies and indicators applied for each of the reviewed models.

Drawing on this model documentation, we subsequently assessed how each subtopic along the cores A) to F) accounts or does not account for the desired features i) to viii) of a new approach in economics. For example, we investigated whether subtopic (4) ‘Pricing’ of the economic structure (core A) is modelled based on heterogeneous agents’ interactions (feature iii of a new economic approach) or includes interdisciplinary knowledge (feature iv).

Table 1: Overview on the evaluated model structures

# 4. Results and discussion

Based on the model inclusion criteria, we identified eleven models. Six among the eleven identified models are large-scale[[11]](#footnote-11) models, including econometric, system dynamics (SD) and agent-based models (ABM). The remaining five models are stylized[[12]](#footnote-12) mathematical models and include ABM, Stock-Flow Consistent (SFC) and SD models. Table 2 gives an overview of the identified models and the following sub-sections give an overview of the different modelling approaches and theoretical underpinnings. A more detailed documentation of the model structure, along the cores A) to F) can be found in the appendix and full documentation is captured in supplementary data.

Table 2: Overview of the reviewed models

*4.1. Overview on different modelling approaches*

*4.1.1. Macro-econometric models*

Applied econometrics applies econometric methods to real-world data for assessing economic theories, developing econometric models, analysing economic history, and forecasting. Commonly used econometric methods include for example ordinary least square (OLS) (Wooldridge, 2006 and see MEDEAS-model) or cointegration (Granger, 1986 and see E3ME-model). Econometric methods require often linear relationships between the independent variable and the dependent variable(s), specify specific requirements (e.g. independence) between the different independent variables or these variables and the error term. Various tests are applied in order to assure that these requirements hold for the selected variables and equations (e.g. Durbin-Watson test).

Most equations in econometric models are linear or log-linear (Mercure et al. 2018; Oxford Economics, 2017). Two-way causation is econometrically estimated in two ways. First, it can be estimated by a simultaneous equation model in which the dependant variables are functions of other dependant variables (with time lags). Second, vector autoregression (VAR) models are applied to capture linear interdependences among multiple time series. Importantly, macro-econometric models can only include variables for which the required data (e.g. quarterly time series data) exist (Hansen, 2016).

With regard to the features of a new approach in economics the following can be indicated:

1. **Complexity, non-linearity, non-ergodicity and deep uncertainty**: Econometric equations are often represented as linear or log-linear. Non-linear relationships often linearized in order to simplify the econometric estimation. In the short time frame, the numerical coefficients calculated with linear approximation are likely to be valid and thus this linearisation is adequate for short-term periods, but problematic for long-term periods. Econometrics methods estimate economic relationships based on historical data and assume that future relationships can be derived, drawing on these estimates (i.e. non-ergodicity does not apply). Deep uncertainty is represented to the extent that model agents do not possess perfect information on the future and that it is not necessarily assumed that markets converge towards an optimal equilibrium.
2. **Importance of time, path-dependency, lock-in and irreversibility**: Macro-econometric simulation models account for time explicitly. That is, the simulated behaviour varies over time and econometric models are suitable to capture path-dependency, lock-in and irreversibility.
3. **Agents’ heterogeneity and behavioural elements:** Macro-econometric models are generally on the aggregated macro level. It is to some extent possible to disaggregate macro-econometric models by for example estimating different equations for different types of agents (e.g. low vs. high-income earners). However, this is subject to data availability and the model software for econometric models is less flexible when it comes to the representation of agent’s interactions as compared to ABM. Behavioural variables can be included in macro-econometric models to the extent that the required data (or a suitable proxy variable[[13]](#footnote-13)) is available.

**iv - vi)** **Interdisciplinary, social and institutional context; Ethical and moral philosophical aspects:** Macro**-**econometric models can generally include various types of variables as long as the requirement of data is satisfied for these variables or a suitable proxy variable can be identified.

**vii) Finance:** Macro-econometric models are generally not used to represent financial relationships. However, SFC models can be combined with macro-econometric models.

1. **Multiple equilibria/disequilibrium:** Macro**-**econometric models are suitable for capturing multiple equilibria and disequilibrium dynamics (e.g. E3ME-model). The interaction of the different econometric equations in the model determine the model outcome and model trajectory, thus multiple equilibria or disequilibrium is the norm rather than the exception.

*4.1.2. System Dynamics models*

System dynamics (SD) was elaborated by Jay Forrester in the 1960s at MIT and is grounded in the theory of non-linear dynamics and feedback control developed in mathematics, physics and engineering (Forrester, 1958; 1961). SD applies concepts of those disciplines in its modelling approach (e.g. the idea to understand and manage systems through feedback loops draws on control theory from engineering). Originally, SD was applied in industrial engineering (Forrester, 1961; 1958). However, since then its applications have been extended to other areas, including organisation theory, economics, health care, cognitive and social psychology and conflict research (see Sterman, 2000 for case studies). SD has often been applied in interdisciplinary research (e.g. economy-energy or sustainable development analysis) (e.g. Fiddaman, 2002; Meadows, 1972; Sterman, 1982).

Mathematically, SD is a set of linked differential equations simulated by algorithms (Sterman, 2000, p. 903ff.). SD models are frequently represented visually through a stock and flow diagram (SFD) or a causal-loop diagram (CLD) (Sterman, 2000; Barlas, 2007).

With regard to the features of a new approach in economics the following can be indicated[[14]](#footnote-14):

1. **Complexity, non-linearity, non-ergodicity and deep uncertainty**: SD is typically applied to address ‘complex’ and ‘dynamic’ problems (Sterman, 2000; Barlas, 2007). It is in the context of complexity, characterised by various interrelated feedback loops and non-linearities that SD emphasises the importance of the representation of key feedback loops as opposed to investigating the exact value of parameter values. The reason is that model behaviour and policy recommendations are often more sensitive to model boundary scope and inherent model dynamics than to uncertainty in parametric assumption (e.g. Sterman, 2000). Deep uncertainty is represented to the extent that model agents typically do not possess perfect information on the future and that it is not assumed that markets converge towards an optimal equilibrium. In addition, SD model can include any effects or scenarios that experts or case-studies would consider as relevant and in addition, explanatory model analysis (Kwakkel & Pruyt, 2013) can be used to test the variations of a large amount of parameter values systematically.
2. **Importance of time, path-dependency, lock-in and irreversibility**: SD accounts for time, path-dependency, lock-in and irreversibility explicitly. Specifically, as mentioned above feedback loops are key elements of SD and SD highlights that in complex systems small parameter changes can get amplified, due to the reinforcing or positive feedback loops and therefore create lock in and path-dependency.

SD introduces the distinction between ‘stocks’ (i.e. integral or accumulation of flows) and ‘flows’ (i.e. derivative or changes in a stock per time interval) (Sterman, 2000). The stocks can also be used to represent a certain capacity (e.g. resources, carbon budgets, water) (e.g. Meadows, 1972). This makes SD well suited to account and visualise changes in the system, irreversibility and system limits.

1. **Agents’ heterogeneity and behavioural elements:** Similar to macro-econometric models, SD is generally on aggregated level. It is to some extent possible to disaggregate SD models through so-called ‘arrays’ that allow to specify different equations for different types of agent-groups (e.g. low-income vs. high-income earners). However, the possibility to represent agent interactions is less flexible as compared to ABM and the model software is not designed for this purpose. The SD program AnyLogic provides a software environment in which SD models can be coupled with agent-based models. Investigating how the system under consideration really works is a key principle in SD. The understanding of actors’ behaviour and their ‘mental models’ (i.e. how they think or how they take decisions; the role of cognitive limitations, agent’s values or preferences) is considered as key in order to follow this principle (Sterman, 2000).

**iv - vi)** **Interdisciplinary, social and institutional context; Ethical and moral philosophical aspects:** SD is an interdisciplinary approach, drawing on the research that is required to understand how the system, which causes the research or policy problem one aims to understand, functions. Model equations can be informed by various research disciplines and by quantitative data sources, including for example statistics from controlled experiments or econometric studies, or qualitative sources, such as for example case studies, interviews or multi-stakeholder workshops (e.g. Sterman, 2000; Forrester, 1961). Given the above, the SD methodology is well suited to consider social and institutional contexts as well as ethical and moral philosophical aspects, if judged as relevant for the model purpose.

**vii) Finance:** SD can generally be used to simulate the financial system and SD models can also be combined with SFC models (e.g. Yamaguchi, 2013; [Jackson & Victor, 2015](https://www.sciencedirect.com/science/article/pii/S0921800916303202#bb0195), 2016).

1. **Multiple equilibria/disequilibrium:** SD models are suitable for capturing multiple equilibria and disequilibrium dynamics (e.g. MEDEAS model). Indeed, the relative strength of positive and negative feedbacks and the delays involved, can cause the system to oscillate, become stable or unstable, implying that system disequilibrium is the norm not the exception (Sterman, 2000).

*4.1.3. Agent-based models*

ABM represent economies as evolving systems of autonomous interacting agents. Agents can be as diverse and as many as required and include all types of agents, such as consumer, firms or governments (Farmer & Foley, 2009). Model agents act and interact according to (sometimes simple) rules and may continually adapt their rules (and behaviour) in order to maximize their benefits (Tesfatsion, 2003; 2006). The ABM methodology is used to answer research questions from various fields (Tesfatsion, 2003)[[15]](#footnote-15).

With regard to the features of a new approach in economics the following can be indicated[[16]](#footnote-16):

1. **Complexity, non-linearity, non-ergodicity and deep uncertainty**: Interactions between agents can be non-linear, discontinuous or discrete. For example, the behaviour of an agent can be altered discontinuously by other agents or by the modelling environment. Interactions of a sometimes large population of model agents leads to complexity, non-linearity and non- ergodicity on the macro-level. Moreover, ABM allows the replication of higher granularity in comparison to SD and macro-econometric modelling. For example, the EURACE-model includes central banks, commercial and investment banks, goods producer sectors, capital sectors, households and various other economic agents. All of those ‘sectors’ are populations of agents interacting with each other, and thus generating the emergent behaviour of each of these sectors, while also interacting with agents from other sectors. Deep uncertainty is represented to the extent that model agents typically do not possess perfect information of the future and that it is not assumed that markets converge towards an optimal equilibrium. In addition, an ABM can include any scenarios or effects that experts or case-studies would consider relevant.
2. **Importance of time, path-dependency, lock-in and irreversibility**: ABM accounts for time, path-dependency, lock-in and irreversibility explicitly. For example, ABM captures that relatively small changes in policies can lead to qualitatively different outcomes in technology diffusion in the long run, e.g. through technology ‘lock-in’ (Arthur, 1994; 1996 et al.).
3. **Agents’ heterogeneity and behavioural elements:** ABM explains how the macroeconomic variables and phenomena (e.g.GDP) are determined endogenously through the interactions of multiple heterogeneous agents. In that sense, ABM provides the sought-after micro-foundations (i.e. accounts for the Lucas-critique). Importantly, agent behaviour can evolve over time using learning algorithms, thus accounting for an additional behavioural element. Agents in ABM are programmed by using heuristics and various data sources and intend to represent the actual behaviour of agents, observed in the real world.

**iv - vi)** **Interdisciplinary, social and institutional context; Ethical and moral philosophical aspects:** ABM is an interdisciplinary methodology and generally open to include social and institutional context as well as ethical and moral philosophical aspects, if judged as relevant for the model purpose.

**vii) Finance:** ABM models have been applied to simulate the financial system from the bottom-up (i.e. to represent the various interactions of entities in the financial system) and can also be combined with SFC modelling (e.g. EURACE-model). Indeed, the advantage of agent-based SFC models is that these models can include several agents for each sector (e.g. households, firms, banks) and that therefore specific rules for individual agents can be formulated and the interactions between these large agent populations determine the aggregated model behaviour (Nikiforos & Zezza, 2017).

1. **Multiple equilibria/disequilibrium:** ABM are suitable for capturing multiple equilibria and disequilibrium dynamics. Indeed, the interactions between various agents determine the macro-behaviour of the model from the bottom-up as an emergent property, implying that system disequilibrium is the norm rather than the exception.

*4.1.4. Stock-Flow Consistent models*

The beginning of the SFC approach goes back to the pioneering work of W. Godley and J. Tobin in the 1970s. SFC modelling provides an integrated framework for the analysis of both the real and the financial side and their connections in one framework (e.g. Godley & Lavoie, 2016). The interest in SFC-modelling increased in particular after the Great Financial Crisis (GFC) of 2007 as SFC models were able to predict the occurrence of this crises (See Godely, 2012).

SFC models emphasise the importance of consistent accounting of all monetary stocks and flows as well as the representation of financial assets and liabilities. Consistent accounting can lead to relevant conclusions by itself because it introduces certain constraints and decreases the degrees of freedom of economic models.

Specifically, accounting consistency from a SFC modelling perspective means the following (e.g. Godley & Lavoie, 2016):

* *Flow consistency*: Every monetary flow comes from somewhere and goes somewhere. As a result, there are no “black holes” in the system. Further, ‘vertical’ flow consistency implies that all transactions involve at least two entries, usually referred to as ‘credit’ and ‘debit’ entries.
* *Stock consistency:* The financial assets of an agent or sector are the financial liabilities of another agent or sector. For example, a treasury bond is a liability for the government and an asset for its holder. Consequently, the net financial wealth as a whole is equal to zero.
* *Stock-flow consistency:* Every flow leads to a change in one or more stocks. As a result, the stock values at the end of the period are obtained by cumulating the relevant flows.
* *Quadruple entry:* The three principles introduced above, then, lead to a fourth principle. That is, every transaction involves a quadruple entryin accounting. For example, when a firm sells a product to consumer, the accounting registers an increase in the income of the firm and in the expenditure of the household. At the same time there is a decrease in at least one asset (or increase in a liability) of the household and a corresponding an increase in at a least one asset of the firm.

The SFC modelling approach goes beyond simple accounting. The second characteristics of SFC model concerns the behavioural specification and the closure of SFC models (e.g. Nikiforos & Zezza, 2017). SCF models are typically characterised with a post-Keynesian model closure, meaning that production is demand-led and that Say’s law, full employment or cleared markets are not assumed[[17]](#footnote-17).

We argue that it depends with what other modelling approach SFC models are combined to what extent the desired features of a ‘new economic approach’ are represented in SFC models. The key asset of the SFC modelling approach lies in the representation of the financial side and the interrelations with the real side of the economy (corresponding to feature vii ‘finance’).

*4.1.5. Overview on modelling approaches*

Based on the explanations above, the Table 3 gives an overview on how the different modelling approaches compare with regard to the ability to capture the different features desired by a new approach in economics. We highlight that the table refers to the potential of the different modelling approaches and that therefore current models of these types do not necessarily always capture these features. The last column of the table indicates why these features are relevant in the context of a low-carbon energy transition.

Table 3: Overview on evaluated features compared to the potential of different modelling approaches to capture them

*4.2. Theoretical underpinnings of modelling approaches*

The above introduced modelling approaches can be applied based on different schools of economic thoughts as theoretical underpinning, including but not limited to, Post-Keynesian Economics (Fontana & Sawyer, 2016), Ecological Economics (Costanza, 1992; Daly & Farley, 2011) complexity economics (Antonelli et al. 2011; Arthur, 1999) or evolutionary economics (Dosi & Nelson, 1994; Fagerberg, 2003)[[18]](#footnote-18).

According to Lavoie (2014), the different non-equilibrium or heterodox economics schools of thought focus on analysing different parts or mechanisms of the economy. In the sense that they conduct ‘work-sharing’ in the analysis of the entire economy. Importantly, the different schools of thought of ‘heterodox’ economics share common presuppositions. That is, they share ‘a set of commonly held metaphysical beliefs, which cannot be put in a formal form, and which are interior to the constitution of the assumptions that rule specific models’ (Lavoie, 2014, p.11). For example, most non-equilibrium economics approaches and in particular post-Keynesian economics recognise modern economies as monetary production economies and understand the economy as influenced by institutions such as governments or labour unions, and they also underline the importance of the concept of ‘deep uncertainty’ (Lavoie, 2014; Sawyer & Fontana, 2016). Moreover, heterodox economic schools of thought share a common view on ontology (e.g. the world is perceived as complex) and epistemology (e.g. actors possess incomplete information) (see below and Lavoie, 2014 for further details).

Given the above, it becomes clear that certain features of a new approach in economics are not only influenced by the chosen modelling approach but also by the theoretical underpinning. As mentioned above, the economic school of thought influences the model structure and basis for the chosen equations.

This is explained in more detail in the following:

1. **Complexity, non-linearity, non-ergodicity and deep uncertainty**: As explained above, heterodox economic theories argue that the world is characterised by complexity, non-linearity, deep uncertainty and non-ergodicity. However, by definition any theory cannot capture deep uncertainty entirely (i.e. the unknown unknowns).
2. **Importance of time, path-dependency, lock-in and irreversibility**: Similarly, time, path-dependency, lock-in and irreversibility is acknowledged by heterodox economic theory.
3. **Agents’ heterogeneity and behavioural elements:** Non-equilibrium theories investigate how agents in a complex world take decisions, having access to incomplete information and possessing limited procedural capacity to understand available information.

**iv - vi)** **Interdisciplinary, social and institutional context; Ethical and moral philosophical aspects:** Institutional economics emphasises the importance of institutions, feminism economics investigates the role of gender in economics or political economy sheds light on the interrelation between the political system and the economics. That is, overall, heterodox economics is open to various other disciplines relevant to understand different parts of the economy. This means that ethical and moral philosophical aspects can be considered for example to balance different policy-objectives in the occurrence of trade-offs.

**vii) Finance:** Post-Keynesian economics in particular emphasises the concept of ‘endogenous money creation’ (i.e. that commercial banks can increase their money supply) and that where the real and the financial side of the economy matter for each other both (e.g. changes in the central bank rate impacts real variables) in both the short and long run.

1. **Multiple equilibria/disequilibrium:** Non-equilibrium theory considers the occurrence of disequilibrium and multiple equilibria the norm rather than the exception, drawing on feature i).

*4.3. Summary of findings*

Due to limited space, our systematic review of energy-transition simulation models is presented in the appendix and the full documentation of the reviewed models is included in the supplementary material of this paper.

In the following, we summarize the insights based on our systematic model review with regard to the desired features of a new approach in economics:

1. **Complexity (incl. non-linear dynamics, tipping points, non-ergodicity and deep uncertainty):** overall, all the reviewed models are based on an ontology and epistemology in line with complexity. In particular, all the reviewed models include agents which do not possess perfect information and foresight, but instead base their behaviour on current or past information of the ‘model-world’. Most of the reviewed models include non-linear dynamics and tipping points. In most of the reviewed models, scenario testing allows to test, to some degree, the impact of uncertainty on policy evaluation. However, as ‘deep uncertainty’ also includes the ‘unknown unknowns’ (Knight, 1921) it is by definition not possible to include this concept into any model or concept. Moreover, some models use econometrics to quantify behavioural equations, which does not account for non-ergodicity of future behaviour. Other models, such as system dynamic or agent-based models include expert knowledge to inform behavioural equations, which is more suitable to account for non-ergodicity, but brings with it the challenge of parameter quantification. A similar limitation applies to the integration of complexity related to ‘comprehensiveness’ into models. Models are by definition abstractions of reality and as such not thought to represent the full complexity of the world. Indeed, there is often a trade-off between simple and clear models versus models that are comprehensive and often more difficult to understand (e.g. Sterman, 2000).
2. **Importance of time, path-dependency, lock-in and irreversibility:** All of the reviewed models are simulation models and therefore time is important by definition. The reviewed models also represent irreversibility, for example, once resources are depleted, they are not renewed. The reviewed models account for path dependency and lock in, for example with regard to technological change (e.g. learning effects in the energy supply sector or the simulation of productivity based on the endogenous accumulation of capital). However, the representation of institutional path-dependency or lock-in is absent in the reviewed models and could be considered in future model-building advancement (see below, feature v).
3. **Agents’ heterogeneity and behavioural elements**: While some of the reviewed models are agent-based models (e.g. EURACE) that represent interactions of heterogeneous agents from the bottom-up, other models, including system dynamics models (e.g. MEDEAS) or macro-econometric models (e.g. E3ME) represent only the aggregated behaviour of agents. However, while the latter models do not represent the interactions of heterogeneous agents from a bottom-up perspective, they do not assume representative agents and hence are still in line with the concept of heterogeneous agents. However, the empirical validation of the interactions of heterogeneous agents is still an important challenge due to a lack of data on the disaggregated level. The increasing emergence of data on a very granular level and machine learning techniques might bring new opportunities for the investigation of behaviour on the micro-level and the connection of the micro, meso and macro behaviour in macroeconomic models. Furthermore, only the EIRIN model considers the role of investor expectations on the possibility to upscale green finance and financial system stability. The representation of expectations, for example subsequent to the introduction of climate policy, of key actors, such as investors, banks and innovators (e.g. related to energy technologies or storage and intermittency possibilities), are however relevant elements that can drive and enable a low-carbon transition (see also below feature vii). Therefore, we recommend their representation in energy-transition models as a future research task.
4. **Interdisciplinary aspects**: Most models include knowledge from other disciplines, such as psychology, behavioural economics or engineering (e.g. inclusion of inventories as buffer or the agent’s use of heuristics). However, the inclusion of interdisciplinary aspects into a macroeconomic model is certainly a field for further research. It could for example be an opportunity to use knowledge from neuroscience for the simulations of agent’s behaviour in economic modelling. Moreover, most of reviewed the energy-transition models include in their model base-run the assumption of no climate change damage, however, research in the field of climate science clearly shows that this is not a likely under the current economic trajectory. Therefore, we recommend the inclusion of more realistic model base-runs that account for climate damages, possibly in a standardised way, on the real economy in future energy-transition models. However, overall, the inclusion of interdisciplinary knowledge into economic modelling touches at some point also the question on where to set the boundary of economic modelling.
5. **Role of institutions and social context**: Most models consider a variety of different policy instruments ranging from taxes to regulations or quantitative easing. However, we recommend future model builders to further expand their model frameworks alongside the inclusion of key actor’s expectations and behaviour such that future energy-transition models allow investigating policy effects on the real economy (e.g. GDP, employment, inequality), the financial system (e.g. stability of the financial system, increase in green investing, see feature viii) and the environment (e.g. emissions). This in turn would lead to a better understanding on how different institutions (e.g. Central banks, financial regulatory authorities and governments) can improve their policy coordination in order to achieve different environmental, economic and financial policy objectives at the same time. Furthermore, the importance of the institutional context is also reflected in the wage rate equation in most of the models. A possibility for further inclusion of the importance of the institutional structure of the economy could be the inclusion of institutional path-tendencies related to vested interests and power imbalances, which can play an important role in (energy system) transitions (e.g. Bolton & Foxon, 2015a; b).
6. **Ethical and philosophical aspects**: Overall, none of the reviewed model would be suitable to optimize the amount of carbon reduction based on the optimization of the costs of emission reduction measures and future damages from climate change on the economy by using discount rates. That is, those models allow for the discussion of ethical and philosophical aspects related to the question of climate justice between current and future generations. However, while the reviewed models leave space for ethical and philosophical judgement it is an important question for the future on how to connect ecological macroeconomic models further with ethical and philosophical aspects (e.g. related to a just energy transition) or how to use insights from these fields together with results from ecological macroeconomic models to inform policy makers.
7. **Finance**: As described in detail in the sub-section ‘economic core’ the majority of the reviewed models track monetary flows and are stock and flow consistent. These models could in principle be applied for the investigation of climate-related transition risks on financial stability. However, only the EIRIN model has been applied so far to assess the risks of the implementation of climate policies on financial stability (Dunz et al., 2018). The representation of actors situated the financial system (e.g. investors, banks) and their expectations (e.g. with regard to future returns of brown vs. green assets) and actions (e.g. increase in green investing) subsequent to the introduction of climate policies is only at its infantry (see EIRIN in Dunz et al., 2018). This representation is however relevant in the context of low-carbon transitions as expectations and decisions of financial actors can impact on the stability of the financial system (e.g. through changes in asset values and the subsequent stranding of assets) and the economic system (e.g. changes in access to credit of firm or in the cost of capital). In addition decisions of financial actors (e.g. investors, banks) can drive and enable a green energy transition as they influence the possibility and costs to upscale finance in renewable energy infrastructure, which required for the decarbonisation of the energy system. Therefore, a more detailed inclusion of ‘finance’ alongside the representation of key actors’ expectation and decisions in the financial system into ecological macroeconomic energy transition models is recommended as an important endeavour for future research.
8. **Multiple equilibria/disequilibrium**: All the reviewed models are simulation models and abstract away from the assumption that markets converge to a long-term equilibrium in the notion of cleared markets.

Overall, while the reviewed models are consistent with a new approach in economics, there is certainly room for improvement (see above). Further, importantly, we do not suggest that quantitative models could, or should, necessarily be the only tool informing policy-makers on economics; instead, we suggest that robust qualitative tools and insights from various research fields could complement results and conclusions drawn from macroeconomics models.

# 5. Conclusions

Our results demonstrate that the 11 reviewed ecological macroeconomic energy transitions models account, to some extent, for the desired features of a new approach in economics. In particular, all reviewed models are grounded in an ontology of complexity and allow for the possibility of multiple equilibria and disequilibrium. All of the reviewed models are simulation models and account therefore for the importance of time, irreversibility and path-dependency. None of the reviewed models relies on rationality; instead, behavioural equations are based on econometrics or simulated though heuristics based on knowledge from behavioural economics or experts. However, interdisciplinary knowledge (e.g. on the impact of climate change on the real economy), ethical and philosophical aspects and the importance of institutions and social context could be included more explicitly (ie. features iv to vi). Alternatively, qualitative or quantitative tools, bringing in these aspects where relevant, could inform policy decisions in addition. Further, six of the eleven reviewed models include a finance sector or are stock-flow consistent. The Investigation of climate-related energy transition risks on the stability of the financial system and the subsequent related feedback-effects on the real economy would in principle be possible by all SFC energy-transition models, but up to date has only been investigated by the EIRIN-model (see Dunz et al., 2018). The representation of the behaviour and expectations of key actors in the financial system relevant for a better understanding of climate-related energy transition risks is only at the beginning (see EIRIN-model, feature III and VII). Relatedly, the inclusion of expectations and decisions of key innovation generators (start-up’s, R&D sector) or adopters (e.g. energy firms) of energy or energy storage technologies for example subsequent to climate policy introduction is another element that warrants refined inclusion in future energy-transition models as innovation is a key driver and enabler of a low-carbon energy transition (feature iii).

We draw two main conclusions. Firstly, we conclude that the reviewed models are relevant for the creation of a new approach in economics. However, to increase their relevance further, we recommend model-builders in the ecological macroeconomics community to (i) to strengthen the integration of the characteristics of a new approach in economics (see above) and (ii) to enhance the comparability across models. The latter is important for the identification of weaknesses and strengths of different models, and of synergies in model advancement by exploiting the model structure or knowledge base of different ecological macroeconomics models. We also recommend future research in the field of ecological economics to focus on the institutionalization of a new approach in economics (i.e. the identification of a (or several) commonly applied macroeconomic frameworks and contribution towards a new approach in economics called for by various institutions).

Secondly, we argue that the reviewed models are policy relevant while exploring the case of the decarbonisation of energy systems. In this context, policymakers are increasingly in urgent need for new long-term planning tools capturing relevant features of modern economies, including for example complexity, uncertainty, non-rationality or disequilibrium. It remains an important question for future research to identify how these models could be applied in a comparable and complementary way, alongside perhaps currently used models. In particular, we recommend the model community to assure comparability of models’ data-sources, structures, theoretical underpinnings, modelling approaches and scenarios so that policy makers and analysts have clarity on how to interpret and compare model results and policy insights coming from different models. Further research should also explore new ways how model builders can communicate their results and policy insights in a meaningful and clear way to decision makers so that they fully understand the relevance of these findings.

Finally, our analysis does not investigate some important questions related to the model assessment and future development in this field. These questions, that should warrant further analysis, include the following: are there unambiguous ‘best solutions’ for specific model structures and could synergies in model-building be better exploited? Is it possible that different ecological macroeconomics models can be connected to each other and if so, what are the benefits of doing so? What types of energy transition policies can be analysed by different models and what are the best approaches to combine and compare evaluations of different models be in order to gain a more comprehensive picture of policy implications? To which extent are policy assessments’ results determined by the model structure? How to assure the transparency and comparability of models’ data-sources, structures, scenarios, results and policy insights?

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1. Another example here is the recent research call of the UK Economic and Social Research Council on Rebuilding Macroeconomics with the objective to create inter-disciplinary and rigorous research that will start to change the economics research agenda (see <https://www.rebuildingmacroeconomics.ac.uk)>. [↑](#footnote-ref-1)
2. INET has been founded in 2009 and is dedicated to the rigorous pursuit of innovative economic theories and methods that address society’s most pressing concerns (INET, 2018a; INET, 2018b). [↑](#footnote-ref-2)
3. We note that this does not mean that we claim that model based on a neoclassical framework cannot account for the features desired by a ‘approach in economics’, however, in order to focus this study and for the reasons explained in section 2, we limit our investigation on simulation models. [↑](#footnote-ref-3)
4. See https://www.oecd.org/naec/ and <https://www.rebuildingmacroeconomics.ac.uk/> for latest updates on the ongoing discussion on new approaches for economic challenges. [↑](#footnote-ref-4)
5. The main difference between our review and the review of Hardt & O’Neill (2017) is that we focus on a systematic review of ecological macroeconomics energy transition models and assesses how they represent the desired features of a new approach in economics. In contrast, Hardt & O’Neill (2017) analyse how different ecological macroeconomic models allow the investigation of post-growth policies. [↑](#footnote-ref-5)
6. We understand ‘ontology’ as the structure of reality and ‘as epistemology’ the theoretical basis on which we understand the world, which involves theories on the origin and limits of knowledge (Spash, 2012). [↑](#footnote-ref-6)
7. For more information on CGE modelling see Dixon & Jorgenson (2013) or Grassini (2009) and see Wing (2007; 2011) or Böhringer & Löschel (2006) for an overview on the CGE models applied for the analysis of Economy-Environment interactions. [↑](#footnote-ref-7)
8. Non-ergodicity means that one cannot rely on current or past average data or behavior to explain or understand what might happen in the future (e.g. Davidson, 1982). This concept has attracted attention with the GFG in 2008 as this crisis was associated with the occurrence of fait tails risks and large changes in expectations and confidence (see Lavoie, 2014). [↑](#footnote-ref-8)
9. These sectors refer to consumption, production, financial or the labour market sectors. [↑](#footnote-ref-9)
10. Thereby, we refer to ‘ecological macroeconomics’ as a relatively new research field that is emerging in the “post-growth” community. Thereby, the main motivation is to investigate the macroeconomic/socio-economic consequences of a low-carbon transition and alternative to economic growth (e.g. de-growth, sustainable prosperity) (see Jackson and Victor, 2016 or Dafermos et al. 2017). [↑](#footnote-ref-10)
11. Large-scale models involve a large amount of variables and equations. These models cannot generally be solved analytical, but are solved numerical. [↑](#footnote-ref-11)
12. Models are considered as stylized mathematical models are if they contain relatively few equations. This type of model is more abstract than large-scale models and does not represent details; instead these models represent main mechanisms relevant for a certain issue. [↑](#footnote-ref-12)
13. A proxy or proxy variable is a variable that is not in itself directly relevant for the estimated relationship, but that is used in place of an unobservable or immeasurable variable. In order for a variable to be a good proxy, it must be correlated, not necessarily linear, with the variable that it replaces. [↑](#footnote-ref-13)
14. See also Papachristos (2019) who describes how SD can be applied for the simulation of sustainability transitions and Köhler et al. (2018). [↑](#footnote-ref-14)
15. LeBaron & Tesfatsion (2008) provide an extensive overview of the use of ABM in economics and the social sciences. [↑](#footnote-ref-15)
16. Safarzyska et al. (2012) shows how evolutionary models, including ABM, can be applied for the simulations of transitions. [↑](#footnote-ref-16)
17. Surveys on the SFC literature can be found in Dos Santos (2006) and Caverzasi & Godin (2014). [↑](#footnote-ref-17)
18. In principle the above mentioned approaches could also be combined with equilibrium theory. For example, SD or ABM could include rational agents. However, this would contradict the SD/ABM methodology that is based on a world-view of complexity (ontology), which implies that model agents cannot possess perfect information (epistemology). [↑](#footnote-ref-18)