# Appendix

This appendix includes the presentation of our systematic model review. We note that some topics of key model cores are not presented here due to increased clarity, but in the supplementary material.

## 1. Economic structure (core A)

### 1.1. Subtopic (1) Role and structure of the market

All models, with one exception, (implicitly) introduce some form of imperfect competition. One exception is EURACE, using a centralized Walrasian market, in its electricity and finance market, but not for its overall economic structure, implying that those two markets converge towards an equilibrium (contradiction of feature viii).

### 1.2. Subtopic (2) Production function

We identified the CES-production function and the use of input-output relationships (with static or dynamic coefficients) as the two main approaches to represent production in our reviewed models (see table A1). The LowGrow SFC model instead does not have a production function per se, but represents the production relationship via capital to output ratio and endogenous labour productivity growth adjusted to capital deepening. The fact that a large number of the reviewed models apply input-output coefficients[[1]](#footnote-1) instead of a CES production function to simulate production might originate from the critique of post-Keynesian (PK)[[2]](#footnote-2) economics and ecological economics on the CES production function. PK-economists mainly point out to limitations in the application of the CES production function because of challenges related to the monetary measurement of capital and the econometric estimation of the CES function, resulting in misleading conclusions (Felipe & McCombie, 2013; Cohen & Harcourt, 2003). Ecological economists argue in particular that energy is a primary requirement for economic production without which production would not take place - a perspective that is not represented by a CES production function as it assumes complementarity between different production inputs, such as labour, capital and energy (Ayres et al., 2013; Kümmel & Lindenberger, 2014). The application of input-output relationships in the reviewed models could have the intention to determine production based on empirical data and to relax the shortcomings of CES production functions described above.

### 1.3. Subtopic (3) Supply or demand-led?

All models, but the T21/SDGi, represent economic output as demand-led, which means that the economy is driven by aggregate demand, including investment, consumption, imports or government expenditures (Fontana & Sawyer, 2016). Table A1 gives an overview. That is, these models do not include mechanisms that lead to full employment and capacity utilisation, thus allowing for the possibility of multiple equilibria or disequilibrium (feature viii). On the other hand, models based on neoclassical theory are driven by the supply-side (i.e. capital and labour), though allowing in certain cases for short-term demand-effects. These supply-driven models generally converge automatically towards an equilibrium that is determined by the amount of capital and labour.

### 1.4. Subtopic (4) Pricing

The LowGrow SFC model and T21/SDGi do not include prices (see table A1). All other reviewed models apply a form of cost-plus pricing for commodities (see table A1). While some models apply a static mark-up factor, other models apply a dynamic mark-up factor dependent on the past market-share and market-structure (S&B, 2017), on market-share only (ENGAGE/DSK) or on productivity gains, variations in capacity utilization, value added tax rates and an exogenous mark-up (EUROGREEN). The way the reviewed models represent prices satisfy the desired features viii, i, iii and iv for a new approach in economics in the several ways: first, this model structure is an example of the fact that those models abstract away from equilibrium as no flexible price adjustment to clear markets is assumed (feature viii). Second, the reviewed models include a model-world, where firms are not assumed to possess perfect information and perfect procedural capacity to calculate the optimal prices. Instead, the way how prices are represented in these models illustrates that firms are not optimizing their profit in the neoclassical sense and based on rationality, but instead apply a simple mark-up pricing rule in a complex world (feature i). Finally, the price-equations of the reviewed models are also an example of a model structure that is based on insights from behavioural economics/psychology (feature iv), as the above explained pricing-rules are a form of heuristics (feature iii).

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Production function** | | | | | | **Demand vs. Supply-led** | | **Pricing** | | |
|  | **Static I/O-coefficients** | **Dynamic I/O-coefficients** | **CES-function** | **AK-growth model** | **CB-function** | **Other** | **Demand-led** | **Supply-led** | **Static Mark-up** | **Dynamic Mark-up** | **Excluded** |
| **E3ME** |  | X |  |  |  |  | X |  | X |  |  |
| **PANTA RHEI/**  **GINFORS** |  | X |  |  |  |  | X |  | X (depends on market structure of each industry) |  |  |
| **MEDEAS** | X |  |  |  |  |  | X |  |  |  | X |
| **T21/SDGi** |  |  |  |  | X |  |  | X |  |  | X |
| **EURACE** | X (E) |  |  |  | X (C&L) |  |  |  | X |  |  |
| **EUROGREEN** |  | X |  |  |  |  | X |  |  | X |  |
| **S&B, 2017** |  |  | X |  |  |  | X |  |  | X |  |
| **ENGAGE/DSK** |  |  |  |  |  | X | X |  |  | X |  |
| **Naqvi, 2015** | X |  |  |  |  |  | X |  | X |  |  |
| **LowGrow SFC** |  | X |  |  |  |  | X |  | Implicitly by the ratio of aggregate demand and supply |  |  |
| **EIRIN** | X (C, L, E) |  |  |  |  |  | X |  | X |  |  |

Table A1: Overview on subtopics (2) Production function (3) Supply vs. demand-led approach and (4) Pricing

### 1.5. Subtopic (5) Investment

A commonality of most models is the inclusion of the variable ‘actual output’ or ‘capacity-utilization’ in the investment equation (see table A2). This equation leads to a mechanism that balances the economy by equalising supply to demand, thus tending to bring the goods market to an equilibrium. However, the convergence to an equilibrium is not given by definition and disequilibrium dynamics are possible (feature viii). Moreover, this mechanism is not based on rationality in neoclassical terms; instead, models firms plan the desired output based on past (e.g. T21/SDGi; EIRIN) or current (e.g. EUROGREEN) sales as proxies for future sales (feature iii). Investments are often also dependent on desired output and on a desired level of inventory. The inclusion of an inventory has a long tradition in PK-economics and in system dynamics and comes originally from management literature (feature iv) (Sterman, 2000; Cincotti et al., 2010; Lavoie, 2014). The presentation of commodity inventories can be interpreted as firms’ preparation towards uncertain demand expectations (feature i). In particular in the model Naqvi, 2015 “firms hold inventories to hedge against any unexpected change in demand” (Naqvi, 2015, p.7). We note that none of the reviewed models includes the a causation from saving to investments, which is a causation that is generally included in neoclassical economics models and based on the assumption of exogenous money supply and perfectly working financial markets leading to an optimal equilibrium (in the long-term) (Lavoie, 2014). The fact that none of the reviewed model includes the above-mentioned causation or a comparable mechanism, demonstrates that they do not necessarily rely on perfectly working financial markets and that their investment function does allow for the possibility of complexity and disequilibrium in the financial markets (feature i and feature viii)[[3]](#footnote-3). All the reviewed models abstract away from the idea that capital could be switched between sectors or sold once it is applied in the production (i.e. they don’t use putty-clay production functions as some CGE-models do (e.g. Dixon & Jorgenson, 2013). That is, the reviewed models account for irreversibility and the importance of time (feature ii) with regard to the installation of capital (e.g. machinery).

### 1.6. Subtopic (6) Unemployment and representation of labour skills

All models which include a labour market account for the possibility of involuntarily unemployment and calculate it as the difference between labour demand and labour supply. MEDEAS is the only model, which does not include a labour market. The inclusion of unemployment in the reviewed models does not rely on cleared markets or rational agents, and is (often implicitly) within a worldview of disequilibrium economics and complexity (feature i and viii). In contrast, the treatment of unemployment in most CGE models is based on the core assumption of rational agents and the idea that the economy is characterized with cleared labour and capital markets and voluntary unemployment in its equilibrium state (Ackerman et al., 2004). Some of the reviewed models differentiate the labour force according to different labour-skills, including the T21/SDGi, EURACE, EUROGREEN and EIRIN model, which is a step towards the inclusion of heterogeneous agents (feature iii) (see table A2).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Unemployment** | | | **Investment function (determination of Gross fixed capital)** | | | | |
|  | **Residual** | **Different skills included** | **Excluded** | **Capacity utilisation/output** | **Interest rates** | **Prices of other inputs** | **Profit/Rate of return/NPV** | **Other** |
| **E3ME** | X |  |  | X | X | X |  | X (labour costs, oil-prices, lagged change in investment) |
| **PANTA RHEI/**  **GINFORS** | X |  |  | x | X |  | X | Capital productivity of the sector and chg. In CPI |
| **MEDEAS** |  |  | X | X |  |  | X |  |
| **T21/SDGi** | X | X |  |  |  |  | X |  |
| **EURACE** | X | X |  | X |  |  | X | Inventory stock |
| **EUROGREEN** | X | X |  | X |  |  | X | Availability of finance |
| **S&B, 2017** | X |  |  | X | X | X |  | Availability of finance |
| **ENGAGE/DSK** | X |  |  | X |  |  |  |  |
| **Naqvi, 2015** | X |  |  | X |  |  |  |  |
| **LowGrow SFC** | X |  |  | X |  |  | X | GDP-Growth |
| **EIRIN** | X | X |  | X |  |  |  | Constrained by credit-availability |

Table A2: Overview on subtopics (5) investment and (6) unemployment and representation labour skills

### 1.7. Subtopic (8) Wage rate

The representation of the wage rate in the reviewed model is an interesting example of the inclusion of complexity (feature i), of behavioural elements (feature iii), the importance of the institutional structure of the economy (feature v) and for the potential requirement of ethical judgement (feature vi). Our reviewed models represent the wage rate generally by using an initial wage rate (given by the data in the base year) and by the variables productivity, inflation rate, desired output and/or unemployment which is sometimes an indicator of union power to calculate the wage rate. In contrast, models based on neoclassical assumptions represent wage rates typically based on the assumption of rational firms that maximize their profits by choosing an output-level where wages-rates (marginal costs) are equal to the marginal productivity of workers, which is derived from the production function[[4]](#footnote-4). Some economists, in particular PK economists, Marxists and institutional economists argue that the wage rate is not equal to marginal productivity necessarily (see Lavoie, 2014). The reason is that on one hand that the institutional and power structure can play an important part in the determination of wages. On the other hand, these economists argue that it would not be possible to derive the marginal productivity from the production function (Lavoie, 2014; Felipe & McCombie, 2013). Moreover, the presentation of wage rates in CGE-models relies on the assumption of rationality, which is typically considered as a flawed assumption by these economists (Lavoie, 2014). As indicated above, none of the reviewed models assumes that rational firms maximize their profits by choosing the wage rate equal to the marginal productivity of labour. Instead, in the reviewed models firms determine their profits by adding a mark-up on top of their units costs[[5]](#footnote-5) (see subsection 4.1.4). This is consistent with a worldview of complexity (feature i) and an understanding that firms are typically using heuristics to make decisions and are not in possession of (near-)perfect knowledge about (future) states of the world (feature iii). Further, one could argue that the way wage rates are simulated in the reviewed model gives room for the interpretation that the economic structure might lead to a situation where the level of wage rates of certain professions or the returns of some assets are not justified by their relative productive contribution to the economy. This in turn could imply that there would be a requirement for ethical judgement on appropriate wage and interest rate levels instead (feature vi). Some models represent the importance of institutions in the treatment of the wage rate (feature v). For example, E3ME includes the unemployment-rate in the simulation of the wage rate to reflect the power of unions in the wage negotiations by explicitly assuming that the power of union is higher when the unemployment is low, and vice-versa (CE, 2019). The table below gives an overview on the variables influencing the wage rate in different reviewed models.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Wage rate** | | | |
|  | **Unemployment** | **Other variables** | **Exogenous** | **Excluded** |
| **E3ME** | X | External industry & regional wage rates, productivity, benefit rate, consumer prices, wage retention rate, normal/actual output and the lagged change in wage rates |  |  |
| **PANTA RHEI/**  **GINFORS** | X | Sector-specific productivity, macroeconomic labour productivity, deflator for aggregate consumption |  |  |
| **MEDEAS** |  |  |  | X |
| **T21/SDGi** |  | Total factor productivity |  |  |
| **EURACE** |  |  |  |  |
| **EUROGREEN** |  | Industry-specific employment, (automation-)technology |  |  |
| **S&B, 2017** |  | Supply and demand of labour |  |  |
| **ENGAGE/DSK** |  | Changes in average labour productivity |  |  |
| **Naqvi, 2015** |  |  | X |  |
| **LowGrow SFC** |  |  | X |  |
| **EIRIN** |  |  |  |  |

Table A3: Overview on subtopic (8) Wage rate

### 1.8. Subtopic (9) Household consumption

Most models include in the consumption equation disposable income and a static or dynamic propensity to consume (see table A4). Importantly, the use of a propensity to consume is not based on the concept of utility-maximizing consumers, but is comparable to the use of a heuristic consumer rule (feature iii). EUROGREEN thereby introduces propensities differentiated by three wage income categories (accounting for feature iii). Furthermore, there are two relevant exceptions that deviate from this general approach. First, EURACE and EIRIN use a desired target-wealth-income ratio of (heterogeneous) model agents to represent consumption. The concept of a wealth-income-ratio is derived from the theory of ‘buffer-stock saving behaviour’, which claims that the consumption/saving behaviour is based on a precautionary saving motive (Carroll, 2011, Deaton, 1992). Second, the S&B, 2017 model represents consumption through the interdependence of preferences of different consumers by including a ‘snob-effect’ and ‘keep-up with the Jones’-effect. In particular, both of those effects are integrated in the utility-function of different consumers. The ‘snob-effect’ reflects a preference to distinguish oneself from the majority through the purchase of status/brand commodities. The network elasticity captures the desire of consumers to imitate choices of others, referred to as ‘network-effect’/’keep up with the Jones’-effect. Importantly, imitation of others leads to cost savings of individual learning, experimentation, or searching by exploiting information already acquired by others. The recognition of the interdependence of utility functions of different agents (or the interdependence of preferences) dates back to Duesenberry (1949) and Veblen (1934), who claimed that social comparison and status seeking are important determinants of individual behaviour (feature iv).

### 1.9. Subtopic (10) Income distribution

Five of the reviewed models represent functional income distribution, but abstract away from the treatment of a personal income distribution (i.e. they do not distinguish between different wage-income categories (see table A4). The remaining six models represent both the functional income distribution and the distribution of personal wage-income categories (feature iii).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Household consumption** | | | | | **Income distribution** | |
|  | **Disposable income** | **Wealth** | **Static Propensity to consume/save** | **Dynamic propensity to consume** | **Other** | **Functional income distribution** | **Wage income distribution** |
| **E3ME** | X | x |  | X | Unemployment on short-term consumption, child dependency ratio, CPI, lagged change in consumers expenditure | X | X |
| **PANTA RHEI/ GINFORS** | X |  |  | X | Nr. of households | X |  |
| **MEDEAS** |  |  | X (labour share instead of real disposable income) |  | Labour-share of GDP | X |  |
| **T21/SDGi** | X |  |  | X |  | X | X |
| **EURACE** | X | X |  |  |  | X | X |
| **EUROGREEN** | X |  | X |  |  | X | X  (3 wage income categories) |
| **S&B, 2017** |  |  |  |  | Interdependence of preferences of consumers (e.g. snob and network effect) | X |  |
| **ENGAGE/DSK** | X |  |  |  | X | X |  |
| **Naqvi, 2015** | X | X | X |  |  | X |  |
| **LowGrow SFC** | X | X (consumption is restricted by the loan-to-income ratio) | X |  |  | X | X(exogenous) |
| **EIRIN** | X | X |  |  | Applies a target-wealth to income ratio | X | X |

Table A4: Overview on subtopics (9) Household consumption and (10) Income distribution

### 1.10 Subtopic (11) Finance and money supply

The treatment of finance and money supply is directly related to the representation of finance (feature vii). The majority of the models includes implicitly or explicitly endogenous money supply. Only one model out of the eleven reviewed models (T21/SDGI) assumes exogenous money supply given by the central bank (see table A5). According to the theory of endogenous money supply, money originates through loans, which are created by commercial banks as long as the borrower is credit-worthy and within some institutional constraints (e.g. Basel III regulations). Therefore, money in the economy is driven by the money demand of bank credit and the credit-worthiness of firms/consumers. In particular, as the demand for loans by the private sector increases, banks normally create more loans and additional banking deposits. Regulation ensures that these loans are only created to a certain multiple of ‘real’ reserves held by these commercial banks. The central bank accommodates the demand for more reserves at the short-term policy interest rate, which is the only variable that the monetary authorities can control. Overall, in that perspective, money can expand and contract independent of central bank policies through the endogenous money creation of commercial banks (Lavoie, 2014; Anger & Barker, 2015). The perspective of exogenous money supply is that money supply is given exogenously by the central bank. The latter perspective is typically adopted by models based on neoclassical theory[[6]](#footnote-6).

Six of the models include finance explicitly (feature vii). That is, either they include an explicit inter-banking sector (see S&B, 2017) or include a commercial bank interacting with firms (EIRIN, EURACE, LowGrow SFC, S&B, 2017; EUROGREEN and Naqvi, 2015) and are stock-flow consistent. In particular, the stylized model S&B, 2017 includes an inter-banking sector and commercial banks issue loans to firms. If firms go bankrupt in this model, there is the possibility that banks go bankrupt too, which leads potentially to instability in the overall inter-banking sector due to the inter-connectedness of commercial banks. The agent-based large-scale EURACE-model includes a very detailed representation of the finance side of the economy. In particular, it simulates money supplied by commercial banks as credit to firms, and it represents fiat money created by the central banks. This makes the model suitable for simulating (green) quantitative easing. As another example, in the stylized model of Naqvi (2015), which includes a finance sector with commercial banks and a central bank, commercial banks give out loans to the production sector. If demand for loans exceed deposits, commercial banks can request advances from the central bank. This then results in the creation of endogenous money. Other models, such as LowGrow SFC or S&B, 2017, include similar mechanisms. EUROGREEN introduces heterogeneous agents, including low-, middle- and high-skilled income earners, with different investment strategies and thus earning different capital returns (related to feature iii). Finally, EIRIN distinguishes between green and brown sovereign bonds in the balance sheet of banks and shows that the green transition can contribute towards the ‘decarbonisation’ of the banks’ balance sheets, which is relevant for the long-term sustainability of the overall bank system. Interestingly as well, the EIRIN-model explicitly considers crowding-in of private investments (due to lower perceived risk) into renewable energy infrastructure when the government provides support for green energy (demonstrating the importance of institutions related to feature v). In principle, all of the SFC-models would allow the investigation of climate-related transition risks on the stability of the financial system and the subsequent induced feedback effects on the real economy. However, only the EIRIN model has been applied up to date for this endeavour (see Dunz et al., 2018; 2019). The extended EIRIN model presented in Dunz et al. (2018) is also the model that represents expectations of investors and banks on asset’s values subsequent to the introduction of climate policies. In this extended EIRIN-version, an equity shares market is introduced in order to capturing investors’ portfolio choices depending on firms’ expected performance in the brown and green sectors. In addition, commercial banks adjust their lending conditions (interest rates) for loans with respect to expected firms’ debt to equity ratios. EIRIN simulations then show that the inclusion of these expectations are relevant in understanding climate related transitions risks of climate policy introduction on financial system’s stability.

Four of the reviewed model (i.e. E3ME, PANTA RHEI/GINFORS, MEDEAS and ENGAGE/DSK) do not include a finance sector and adopt implicitly endogenous money supply approach. That is, the available money is not assumed to be controlled by the central bank and firms can borrow freely from commercial banks as long as they are perceived as credit-worthy and within the given regulatory framework. These latter two restrictions are explicitly represented in some of the models (e.g. E3ME; LowGrow SFC; EUROGREEN).

### 1.11. Subtopic (12) Interest rates

The reviewed models represent average interest rates neither based on the assumption that they are equal to marginal capital productivity in equilibrium nor that financial markets are necessarily in equilibrium, thus allowing for disequilibrium (feature viii). Current research in the field of behavioural economics (e.g. De Bondt & Thaler, 1995), but also already Keynes (1964) and other post-Keynesian economists (see Lavoie, 2014) pointed out that interest rates are influenced by expectations of various market participants which influence each other. This mechanism is not represented explicitly in the reviewed models and capturing it could be a way for future model advancement in this area. Some models (e.g. EURACE and EIRIN) introduce different spreads on the average interest rates for the cost of capital of green vs. brown capital.

The table below gives an overview on the variables influencing the interest rates in the reviewed models.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Treatment of Finance** | | | **Simulation of the avg. interest rate** | | | |
|  | **Implicit inclusion of endogenous money supply** | **Includes finance in the model and assumes endogenous money supply** | **Implicit exogenous money supply** | **Exogenous mark-up of the CB-rate** | **Other (endogenously)** | **Exogenously given** | **Excluded** |
| **E3ME** | X |  |  | X |  |  |  |
| **PANTA RHEI/**  **GINFORS** | X |  |  |  | X (lending & borrowing of institutional transactors, US interest rates for government bonds) | X (for countries of the EURO area) |  |
| **MEDEAS** | X |  |  |  |  |  | X |
| **T21/SDGi** |  |  | X |  | X (influenced on aggregated level by the level of debt in the economy) |  |  |
| **EURACE** |  | X (SFC, inclusion of commercial banks) |  |  | X (credit-worthiness) |  |  |
| **EUROGREEN** | X (inclusion of different types of assets (.e. bonds, equity)  In which different actors invest |  |  | x |  |  |  |
| **S&B, 2017** |  | X (Inclusion of interbank lending market and debt of firms, tracks financial flows) |  |  |  | X |  |
| **ENGAGE/DSK** | X |  |  |  |  | X |  |
| **Naqvi, 2015** |  | X (SFC, inclusion of commercial banks) |  |  |  | X |  |
| **LowGrow SFC** |  | X (SFC, inclusion of commercial banks) |  | X |  |  |  |
| **EIRIN** |  | X (SFC, inclusion of commercial banks) |  |  | X (debt-to equity ratio of firms) |  |  |

Table A5: Overview on subtopics (11) Finance and money supply, and (12) interest rates

## 2. Technology treatment (core B)

### 2.1. Subtopic (1) Productivity

In general terms, most of the models include the impact of capital (EUROGREN), or more specially R&D capital (E3ME; T21/SDGi; S&B, 2017; LowGrow SFC; ENGAGE/DSK) on labour productivity (see table A6). This means that endogenous growth and path-dependency is included in those models (feature ii). Most models allow the testing of the impact of policies on technological change (e.g. by allowing them to impact R&D or capital investments, which afterwards impact directed productivity changes) (related to feature v). EUROGREEN represents technological change driven by ‘automation technology’ by introducing capital that substitutes middle-skill work, but complements high, and to some extent low, skill work. This adds some heterogeneity in the representation of technological change (feature iii). S&B, 2017 represents individual firms that engage in a search process for better technological solutions through R&D activities or by copying the industry's best practices (also integrating feature iii). See table A6 for an overview. As it concerns future model building, it could be interesting to expand the model structure to represent potential interrelations of institutional structure and technological change, in particular related to inventions and ‘market-shaping’ policies (see Mazzucato, 2016), thus integrating feature v more explicitly into the presentation of technological change).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Total factor productivity** | | | **Labour productivity** | | | **Energy efficiency** | | |
|  | **Endogenous** | **Exogenous** | **Excluded** | **Capital or R&D Investments** | **Other** | **Exogenous** | **Endogenous** | **Exogenous** | **Excluded** |
| **E3ME** | Technological progress: Investment and R&D expenditures |  |  | X |  |  |  | X |  |
| **Panta Rhei /**  **GINFORS** |  |  | X |  | Real wage rate and technological trends |  | Cost-push and time-trend |  |  |
| **MEDEAS** |  | GDP-growth-trend |  |  |  | X | Price pressure (due to energy scarcity) - transport sector |  |  |
| **T21/SDGi** | Macro-stability, openness to trade, energy prices, governance, climate change, education, health, access to electricity, female participation and transportation infrastructure |  |  | X | Education, cost of technology/cost of labour vs. energy, global avg. Technology level |  | Cost of technology, cost of labour vs. energy, global avg. Technology level |  |  |
| **EURACE** | X (quality of capital and skills of workers) |  |  |  | Individual learning effects dependent on skills and produced output |  |  | X |  |
| **EUROGREEN** |  |  | X | X | - technical change Increases of labour productivity, substitutes middle-skill and complements high-skill workers  -driven by labour costs and Innovation |  | Energy-costs |  |  |
| **S&B, 2017** | Firms engage in a search process for better technological solutions through R&D activities or by copying the industry's best practices |  |  | X |  |  | X |  |  |
| **ENGAGE/DSK** |  |  | X | X |  |  | R&D investments |  |  |
| **Naqvi, 2015** |  |  | X |  |  | X |  | X |  |
| **LowGrow SFC** |  |  | X | X |  |  | Investments in brown vs. green capital |  |  |
| **EIRIN** |  |  | X |  |  | X |  | X |  |

Table A6: Overview on the models’ core B (Technology treatment)

## 3. Treatment of agent’s behaviour and time (core C)

### 3.1. Subtopic (1) Models’ ontology

All models adopt an ontology of complexity and deep uncertainty, and abstract away from the assumption that model agents are rational i.e. that they have (near) perfect foresight and the capacity to proceed all available information (feature i and iii). It is important to mention that while our sample of reviewed models includes only models based on a world-view of complexity and deep-uncertainty (feature i), it nevertheless does not mean that (especially stylized) models are necessarily complex or comprehensive with regard to their model structure.

### 3.2. Subtopic (2) Representation of behavioural equations

Behavioural equations of reviewed models are based on econometrics and empirical data, on the use of research studies, on expert’s opinions and on heuristics that are derived from literature, including, but not limited to, management or psychological literature (feature iii and iv). With regard to the use of heuristics, in some of the reviewed agent-based models (e.g. EURACE or S&B, 2017) it is assumed that agents possess the capability to learn over time, that their heuristics adapt over time and enable the agents to reach better outcomes. The model S&B, 2017 also provides a relevant example on how to integrate insights from behavioural economics as it considers the interdependency of consumer preferences (see for more information the paragraph on the consumption core earlier. The inclusion of expert opinion into models helps to partly account for non-ergodicity (feature i). Here, the challenge lies, however, in the parameterization of impacts considered as relevant by expert judgements. Overall, behavioural equations in the reviewed models only rely on past or actual data, and agents form their expectations only based on information available in a complex world (feature i).

### 3.3. Subtopic (3) Treatment of heterogeneity of agents and interactions between them

Six of the reviewed models (i.e. E3ME, Pantha Rhei, MEDEAS, T21/SDGi, EUROGREEN, LowGrow SFC, EIRIN and Naqvi, 2015) are on aggregated level and agents (e.g. consumers/firms or different industries) do not interact from the bottom-up. This means that the macro-behaviour (on sectoral level/per agent-type) of the model is not derived from micro behaviour or bottom-up interactions explicitly. However, the aggregated behaviour (of each sector/agent-type) of these models is not based on deductive reasoning and neither on the assumption that all agents are homogenous, which is an assumption typically adopted by CGE models (see Kirman, 1992 for a discussion)[[7]](#footnote-7). The table below gives an overview on the treatment of agents’ behaviour in the reviewed model sample.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Simulation of behavioural equations** | | | | **Heterogeneity of agents/interactions of agents** | |
|  | **Econometric estimations** | **Econometric studies or other studies** | **Expert knowledge** | **"Heuristics"** | **Aggregated/sectorial level** | **Heterogeneous agents and interactions between them** |
| **E3ME** | X | X |  |  | X |  |
| **PANTA RHEI/**  **GINFORS** | X |  |  |  | X |  |
| **MEDEAS** | X | X | X |  | X |  |
| **T21/SDGi** | X | X | X | X | X |  |
| **EURACE** |  |  |  | X |  | X |
| **EUROGREEN** | X | X |  | X | X |  |
| **S&B, 2017** |  |  |  | X |  | X |
| **ENGAGE/DSK** |  |  |  | X |  | X |
| **Naqvi, 2015** |  |  |  | X | X |  |
| **LowGrow SFC** | X | X |  | X | X |  |
| **EIRIN** |  |  |  | X | X |  |

Table A7: Overview on the models’ core C (Treatment of agents’ behaviour)

### 3.4. Subtopic (4) treatment of time

All models include the notion of ‘time’ explicitly and include irreversibility and path-dependency respectively (feature ii). The treatment of productivity or capital are examples for this claim. However, the consideration of path-dependency or lock-ins due to institutional structures is an element that is absent in the reviewed model (as explained in more detail in section 4.4. below).

## 4. Appearance of government and central bank (core D)

### 4.1. (1) Role of the government and (2) Role of the central bank

Most reviewed models track government income and expenditure, and allow the implementation of a variety of other policies beyond carbon-taxes including for example Feed-in-Tariffs or R&D-investments (see table A8). None of the models captures any potential implementation challenges with regard to different policy implementation strategies (e.g. resistance from society or the corporate world. However, given the complexity of policy intervention processes, especially in the case of complex large-scale transitions, affecting various stakeholders, this could be relevant to represent.

In most models, the central bank sets the policy interest rate exogenously or through some form of a Taylor-rule (see table A8). In some models the central bank provides liquidity to commercial banks (e.g. EIRIN, EURACE, LowGrow SFC, EUROGREEN, S&B, 2017 or Naqvi, 2015), or acts as an ‘arm of the government’ (e.g. EURACE, EIRIN or Naqvi, 2015) (feature v).

Overall, the representation of the government and the central bank in the reviewed models shows that these models attribute importance to the government and the central bank as institutions (feature v). In particular, the reviewed models allow the testing of a larger variety of policies than ‘carbon taxes’, which is typically the only testable policy instrument in most CGE models[[8]](#footnote-8). Further, EURACE allows also the testing of quantitative easing policies and EIRIN the issuance of green sovereign bonds or the introduction of a green supporting factor. These examples demonstrate that both the government and the central bank have a potential role to play to decarbonise the energy sector (feature v). With regard to improvement of the integration of feature v, our reviewed model sample does not shed light on the role of institutional path-dependency (e.g. related to vested interests and power imbalances) in the ‘green’ energy transitions (see Bolton & Foxon, 2015a). Further, the role of institutions in ‘market-shaping or –creating’ policies is not clearly represented, although it could be relevant in the discussion on long-term energy transition (see Mazzucato, 2016).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Government** | | | **Central bank** | | | |
|  | **Treatment of policies: Implementation challenges of policies are not accounted for in the model** | **Captures Government income and expenditure** | **Other policies than carbon price is simulated in the model** | **Sets interest rate** | **Provides money to commercial banks/lender of last resort** | **No role assigned** | **Other** |
| **E3ME** | X | X | X | X |  |  |  |
| **PANTA RHEI/ GINFORS** | X | X | X | X |  |  |  |
| **MEDEAS** | X |  | X |  |  | X |  |
| **T21/SDGi** | X | X | X | X |  |  |  |
| **EURACE** | X | X | X | X | X |  | X (Quantitative easing) |
| **EUROGREEN** | X | X | X | X | X |  |  |
| **S&B, 2017** | X |  | X |  | X |  |  |
| **ENGAGE/DSK** | X | X |  |  |  | X |  |
| **Naqvi, 2015** | X | X |  |  | X |  | X (Quantitative easing) |
| **LowGrow SFC** | X | X | X | X | X |  |  |
| **EIRIN** | X | X | X | X | X |  |  |

Table A8: Overview on the models core D (Appearance of government and central bank)

## 5. Energy supply sector (core E)

### 5.1. Subtopic (1) General information

All large-scale simulation models include the explicit representation of more than five primary energy sources and energy-production technologies in the energy supply core (table A9). The stylized models often include only three or two energy-types (high, middle and low/zero carbon energy-sources).

### 5.2. Subtopic (2) Market-shares of energy technologies

Most of the reviewed models simulate the market-share of different technologies as dependent on the net-present-value or the unit costs of different energy-producing technologies, with costs dependent on learning effects (E3ME, EURACE, Pantha Rhei and ENGAGE/DSK) or changes in energy returned on energy invested (EROI) (E3ME, MEDEAS). Therefore, technological change in the energy supply sector is mostly simulated endogenously and includes path-dependency and network effects (feature ii).

### 5.3. Subtopic (3) Technical constraints

Around half of the models include some sort of (technical) constraints with regard to the expansion of non-renewable or renewable energy infrastructure. There are many different technical constraints, including constraints with regard to land-use, availability of wind, availability of non-renewable energy-sources, availability of material for construction of energy infrastructure (e.g. rare metals/resources) or limits with regard to a market-share of renewable energy sources due to intermittency and network stability issues. In particular, E3ME and MEDEAS include a large amount of energy expansion constraints both with regard to renewable and non-renewable energy. Both models include limits to availability of non-renewable energy sources, land-use and other expansion constraints with regard to renewable energy and MEDEAS also includes the required material for the production of renewable energy production infrastructure.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Primary energy** | | **Simulation of the market-share of each technology** | | | **Simulation of costs of renewable energy** | | | **Simulation of constraints** | | | |
|  | **Yes** | **No** | **(LCOE)/NPV** | **Other** | **Exogenous** | **Learning rates** | **EROI** | **Exogenous** | **Availability of primary energy** | **Renewable energy constraints** | **Material constraints** | **Not considered** |
| **E3ME** | X |  | X | X |  | X | X |  | X | X |  |  |
| **Panta Rhei GINFORS** | X |  | X |  |  | X |  |  | X | X |  |  |
| **MEDEAS** | X |  |  | X | X |  | X | X | X | X | X |  |
| **T21/SDGi** | X |  | X |  |  |  |  | X | X | X |  |  |
| **EURACE** | X |  | X |  |  | X |  |  |  |  |  | X |
| **EUROGREEN** | X | X |  |  | X |  |  | X |  |  |  | X |
| **S&B, 2017** |  | X | X | X |  |  |  | X |  |  |  | X |
| **ENGAGE/DSK** |  | X | X |  |  | X |  |  |  |  |  | X |
| **Naqvi, 2015** |  | X |  |  | X |  |  | X | X |  |  |  |
| **LowGrow SFC** |  | X | X |  |  |  |  | X |  |  |  | X |
| **EIRIN** |  | X | X |  |  |  |  | X |  |  |  | X |

Table A9: Overview on the models’ ‘Energy supply core’

## 6. Integration of the Environment (core F)

### 6.1. Subtopic (2) Other relevant information

The evaluated models are generally energy-economics models that capture emitted carbon emissions by the economy but do not account for climate damages caused by the economy. Exceptions to this are the agent-based integrated assessment DSK-model, an extended version of the EIRIN-model (Dunz et al., 2018), the MEDEAS-model and an extended version of the E3M3-model (i.e. E3ME-FTT-GENIE, see Mercure et al., 2018) that accounts for climate change damages on the real economy. However, none of the models applies a discount-rate to calculate the present value of future climate change damages – acknowledging that an ethical judgement is required to set an appropriate discount rate in this case[[9]](#footnote-9) (feature vi) (e.g. in case of the MEDEAS-model see Capellán-Pérez et al., 2017, p. 20). Furthermore, Capellán-Pérez et al. (2017) state that the MEDEAS-model “*follows the strong sustainability-approach and applies the precautionary principle in the light of the high uncertainties and risks of potential disruptive environmental/climate change in the next decades*”.

1. Input-output analysis, both in monetary and physical terms, has been extensively applied in ecological economics models (Hardt & O’Neill, 2017). Monetary input-output data is presented in a matrix and describes the monetary flows between different industries. Input-output coefficients calculated by diving the input by the level of desired output and allow to calculate the amount of inputs required to produce a certain level of output. [↑](#footnote-ref-1)
2. The post-Keynesian framework recognises modern economies as monetary production economies; it recognises the role of fundamental uncertainty and path-dependency and the importance of the interdependency of aggregate demand and aggregate supply in the determination of the long-run output level. Post-Keynesian economics understand the economy as being influenced by institutions, such as governments or labour unions and emphasise as well the concept of ‘deep uncertainty’ on the micro-level (Lavoie, 2014; Fontana & Sawyer, 2016). [↑](#footnote-ref-2)
3. In the case of the reviewed models investments are equal to savings as this is balance account identify, however, no causality is involved in this case (see Lavoie, 2014 for further information). [↑](#footnote-ref-3)
4. Some CGE models include the idea of union-power into the simulation of wage rates. However, they do so based on the initial assumption that the wage rate is equal to marginal productivity (Felipe & McCombie, 2013). [↑](#footnote-ref-4)
5. While some CGE/DSGE models simulate prices as well by a mark-up factor on firms’ unit costs, they nevertheless assign prices a market-clearing mechanism. These models typically assume also that firms calculate mark-ups dependent on the elasticity of demand, implying that profits would be zero in the case of perfect completion and assigning firms optimizing behavior based on the notion of rationality (e.g. Francois, 1998). [↑](#footnote-ref-5)
6. An exception are New Keynesian DSGE models, which also represent money supply endogenously. However, these models nevertheless assume a relationship between the interest rate and the money supply in the economy. In addition, the role of money in this type of model is limited due to the lack of uncertainty and the assumption of complete capital markets (Fagiolo & Roventini, 2016). [↑](#footnote-ref-6)
7. In this study, we would refer to a single firm, consumer as an agent. We refer to the model as an aggregated model if the simulation of behavior of agents or entities from the bottom-up is not included in the model. For more information on the micro-foundations of post-Keynesians economics and the challenge to reconcile micro and macroeconomics, we refer for example to Harcourt (1977; 2008). [↑](#footnote-ref-7)
8. The reason is that in these models all prices are equivalent regardless of how they are achieved (i.e. they do not distinguish between a carbon tax or a trading scheme – if the price is the same). These models allow generally not simulating other types of policies (i.e. policies that do not affect prices). [↑](#footnote-ref-8)
9. See Barker (2008) for a discussion on the discount rate with regard to climate change damage. [↑](#footnote-ref-9)