Environmental-macroeconomic modeling: Notes from the field

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Abstract

There is a demand for models that link environmental impacts and macroeconomic processes. By far most of the existing models embody neoclassical economic assumptions, but the pragmatism of both environmental specialists and policy analysts invites other approaches. This paper describes energy-economy and water-economy models in broad terms and reviews some of the major existing models. It then offers reflections based on the author's own experience developing policy-focused environmental-macroeconomic models. The paper concludes by noting potential contributions by post-Keynesian, Sraffians, and others working outside the dominant neoclassical paradigm.

1 Introduction

In 1975, the Cocoyoc Declaration (UNEP/UNCTAD 1975) called out the continued failure to meet human needs and rising environmental pressures:

> Thirty years have passed since the signing of the United Nations Charter launched the effort to establish a new international order. Today, that order has reached a critical turning point. Its hopes of creating a better life for the whole human family have been largely frustrated. It has proved impossible to meet the "inner limit" of satisfying fundamental human needs. On the contrary, more people are hungry, sick, shelterless and illiterate today than when the United Nations was first set up. At the same time, new and unforeseen concerns have begun to darken the international prospects. Environmental degradation and the rising pressure on resources raise the question whether the "outer limits" of the planet's physical integrity may not be at risk.

The overarching goal of balancing human well-being against finite resources remains a recurring theme. Most recently the outer environment limits have been codified in a set of "planetary boundaries" (Rockström et al. 2009; Steffen et al. 2015). The space between those outer limits and the inner limit of human needs has been dubbed the "doughnut" (Raworth 2017) and investigated as the locus of a "good life for all within planetary boundaries" (O'Neill et al. 2018; Fanning et al. 2022).

The achievement of a good life for all within planetary boundaries is the central challenge of our time, and as an ultimate goal should be continually kept in view. Key analytical questions are, "What could such a society look like?" and "How can we get from here to there?" However, those questions are too large for most policy processes. In high income countries a lesser but still helpful question is, "How can we rapidly reduce high environmental burdens while supporting those most affected by the transition?" In low and middle income countries a reasonable question is, "What can we do now to better meet human needs without placing undue additional burdens on the environment?" These are the questions addressed by research on environment-economy links.

Within the broad area of environment-economy interactions, this paper specifically addresses the design of environmental-macroeconomic policy models. Such models can be placed in two broad categories: those that started as biophysically-based models and added economic elements ("bottom-up" models); and those that started as economic model and added environmental elements ("top-down" models). More recently, "hybrid" models have sought to benefit from the strengths of each of the two broad designs (Hourcade et al. 2006).

As in most areas of economic policy analysis, the bulk of existing models are informed by neoclassical theory. To be sure, natural resources and environmental impacts have been introduced in post-Keynesian (e.g., Fontana and Sawyer 2016), Sraffian (e.g., Scazzieri, Baranzini, and Rotondi 2019), and classical (Foley, Michl, and Tavani 2019, chap. 18) theory, while Dafermos et al. (2017) embed environmental accounts within a stock-flow consistent (SFC) model. Indeed, resource constraints were an overriding concern of classical authors, who brought theoretical insights to policy debates of the early 19th century (Pasinetti 2019). However, the focus of this paper is on contemporary economic policy analysis, where uptake of non-neoclassical approaches has so far been modest. Some of the exceptions will be discussed below.

This paper is written from the author's perspective, while referring to the broader literature on environmental-macroeconomic policy models. The author's work focuses on energy-economy, water-economy, and water-energy-food-ecosystem (WEFE) "nexus" models for low- and middle-income countries. Given that focus, this paper will not cover the important class of climate-economy models, of which there are many examples, supported by an extensive literature (e.g., see Bernard and Semmler 2015). Nevertheless, by themselves water and energy raise important issues, including the role of resource constraints and the need for sectoral and geographic detail.

Section 2 provides some background to environmental-economic models. Section 3 offers some general considerations for constructing such models. Section 4 surveys the types models in wide use today. Section 5 offers some "notes from the field" based on the author's experience. Section 6 concludes.

2 Background

The natural environment interacts with the economy at multiple points. The general position of ecological economists is that economies are institutions that sit within societies that are themselves embedded in the natural environment. Economic institutions drive and facilitate the extraction and transformation of natural resources from geological formations and ecosystems in support of social processes, while generating wastes. Further, together with legal institutions, economic institutions control access to the natural environment. Such a position encourages a systems approach, viewing the subject matter as comprised of interlocking, complex open systems, an orientation that is compatible with both post-Keynesian and institutionalist traditions (Vatn 2009, 124). Where ecological and post-Keynesian economics diverge are, first, on the desirability of economic growth as a policy goal, and, second, on the relative scarcity of ecosystem services (Kronenberg 2010, sec. 2.4).

While the term "environment" will be used in this paper, it is important to note that, following the lead of ecologists, many ecological economists – the author included – view "ecosystem function" as a more relevant concept for sustainability (although this term is also contested; see Jax and Setälä 2005). However, for environmental-macroeconomic planning models, the use of the ecologically uninformed term "environment" is arguably appropriate. As made clear by the authors of the draft report on Ecosystem Accounting from the UN Committee of Experts on Environmental-Economic Accounting (UNCEEA 2021), ecosystems are complex. They are place-based dynamic systems that can be viewed from a variety of perspectives: spatial, ecological, societal benefit, asset value, or institutional ownership (p. 26). In contrast, the accepted 2012 version of the Central Framework of the System of Environmental-Economic Accounts (SEEA) focuses modestly on the resource stocks and flows most directly related to economic transactions (UN et al. 2014).[1]

The core set of accounts for SEEA Central Framework are illustrated in Figure 1. As shown, they consist of combined physical and economic accounts, which are linked by prices or price indices. The flows illustrated in the physical supply and use table are constrained by biophysical processes, mediated by technology. These inform modeling choices for biophysically-based resource models. For example, for the flow *natural inputs-supply*, an agricultural model might feature a biological process model for specific crop types combined with water, fertilizer, sowing, harvesting, and post-harvesting technologies; an energy model might include crude oil production, combining geology with extraction technology. Environment-economy models vary considerably in the level of detail they give to the physical accounts.

The economic accounts are conventional, and can be incorporated into any kind of economic model, whether macroeconometric, computable general equilibrium (CGE), dynamic stochastic general equilibrium (DSGE), and others, such as agent-based models (ABM) (see Cohen 2014 for macroeconometric and CGE; for DSGE see Sbordone et al. 2010; for ABM see Tesfatsion 2006). Each of

[1] The SEEA are under continual development. For methodological updates, see https://seea.un.org/content/seea-central-framework.

these types of models has been used to analyze water-economy and energy-economy interactions (Castelli et al. 2022). Environmental accounts have also been combined with Kaleckian models (Okuma 2017). Therefore, any criticism that can be leveled against each of these types of models in general applies with equal force when they are used in environment-economy models. Furthermore, additional critiques may apply having to do with the extent to which they can capture environment-economy links.

						Asset accounts (Physical and monetary terms)	
		Industries	Households	Government	Rest of the world	Produced assets	Environmental assets
						Opening stock	
Monetary supply and use table	Product-supply	Output			Imports		
	Product-use	Intermediate consumption	Household final consumption expenditures	Government final consumption expenditures	Exports	Gross capital	
Physical supply and use table	Natural inputs-supply						Extracted natural resources
	Natural inputs-use	Inputs of natural resources					
	Product- supply	Output			Imports		
	Product-use	Intermediate consumption	Household final consumption		Exports	Gross capital formation	
	Residuals-supply	Residuals generated by industry	Residuals generated by household final consumption		Residuals received from the rest of the world	Residuals from scrapping and dem-olition of produced assets; emissions from controlled landfills	
	Residuals-use	Collection and treatment of waste and other residuals			Residuals sent to the rest of the world	Accumulation of waste in controlled landfills	Residuals flowing to the environment[a]
						Other changes in volume of assets (e.g., natural growth, discoveries, catastrophic losses)	
						Revaluations	
						Closing stock	

Note: Dark grey cells are null by definition. Blank cells may contain relevant flows, which are articulated in detail in chap. III.

[a] While these residual flows (e.g., air emissions) are not flows of environmental assets, they may affect the capacity of environmental assets to deliver benefits. The changing capacity of environmental assets may also be reflected in other changes in the volume of assets.

Figure 1: Connections between SEEA supply and use tables and asset accounts (Source: UN et al. 2014)

Based on general principles, the class of DSGE models is excluded in this paper. After 2008, even DSGE models' defenders start by explaining their substantial weaknesses (Hurtado 2014; Lindé 2018), and DSGE models have been strongly criticized by both post-Keynesian (Marchionatti and Sella 2017) and neoclassical (Solow 2008) authors. What is more, their applications to environmental issues remain somewhat thin (Castelli et al. 2022, tbl. 1).

For other reasons, this paper will not discuss ABMs. Despite the existence of large-scale policy-focused ABMs, such as EURACE (Deissenberg, van der Hoog, and Dawid 2008) and its successor Eurace@Unibi (Dawid et al. 2012), policy-oriented ABMs are highly data-intensive and hence are mainly applied at local scale. For now it is enough to note that ABMs appear consistent with post-Keynesian and classical theory (Di Guilmi 2017; Fanti 2021).

Macroeconometric models follow in the tradition laid down by Lawrence Klein (Klein and Goldberger 1969; Duggal, Klein, and McCarthy 1974) and Richard Stone (Johansen 1985). These models are Keynesian, whether of the "old" Keynesian or post-Keynesian variety.

Computable general equilibrium (CGE) models, as conventionally developed, have significant limitations as well, but they are widely used and represent the dominant "top-down" approach to environmental-macroeconomic modeling. They therefore provide a useful reference for conventional policy analysis.

In his own work, the author follows the "structuralist" tradition of Lance Taylor (Taylor 1989; 1990a; 2004; Ocampo, Rada, and Taylor 2009). The structuralist approach is highly pragmatic, grounded in observed conditions, particularly as reflected in the persistent (but ultimately mutable) structures that shape economic activity. It is also avowedly post-Keynesian in inspiration. This tradition allows for a variety of modeling strategies, including non-neoclassical CGE (Taylor 1990b) and econometrically estimated models. The author's own work is similarly varied, but typically features multiple sectors and dynamic processes unfolding in historical time.

This paper will discuss general issues around energy-economy, water-economy, and related models. It will emphasize potential connections to post-Keynesian, Sraffian, and related theory, with reference to the author's work and to dominant models. For top-down environment-economy models, the paper will discuss macroeconomic and CGE models. For bottom-up models it will discuss a particularly influential bottom-up energy-economy model, ETA-MACRO (Manne 1977), and its successors.

3 General considerations

The focus of this paper is on practical policy modeling. However, applied modelers rely on basic empirical and theoretical developments for the "building blocks" of their models. This section is therefore aimed at both applied modelers and researchers working at more basic levels. It presents some broad issues that arise in nearly all cases when developing environmental-macroeconomic models.

Perhaps the most important consideration is that environmental-macroeconomic interactions are very sector-specific. In Klein's terms, they require "structural" rather than "macro" policies (Klein 1983, 96). This points to at least some degree of sectoral disaggregation. Energy and water modelers are well aware that there are more or less energy- or water-dependent sectors (Gleick 2003; Worrell, Ramesohl, and Boyd 2004; Liu, Hertel, and Taheripour 2016). For example, agriculture accounts for around 70% of freshwater withdrawals globally,[2] a figure that rises to above 90% in several countries.[3] Energy-intensive sectors include transportation, mining, and heavy industry.

A further consideration is that patterns of resource production, distribution, and use vary considerably between resources. For example, a chronic issue with joint energy-water modeling is that electricity grids are not inherently geographically constrained, while water resources are largely confined to river basins or groundwater reservoirs, and both are subject to governance at multiple scales (Scott et al. 2011). The limits of natural basins can be overcome through inter-basin water transfers, but large-scale transfers are usually highly energy-intensive (Gleick 1994).

Furthermore, effective natural resource management may impose constraints that should be taken into account: the need for robust ecosystem function, the role of ecosystems as waste processors, and non-monetary ecosystem services for humans. Regarding the first of these – ecosystem function –

[2] https://www.worldbank.org/en/topic/water-in-agriculture
[3] https://www.fao.org/aquastat/en/

environmental flow requirements may be introduced as constraints in water models (Pastor et al. 2014), while energy-water models may restrict outflows of cooling water from thermal power plants (Vliet, Vögele, and Rübbelke 2013).[4] Regarding the second, discharge of water after use by humans normally entails some degree of pollution (Chapra 2008), while fuel combustion generates hazardous by-products.[5] Regarding the last issue, people value ecosystems for aesthetic, spiritual, or other non-market reasons. Models may impose constraints on expansion, e.g., for protected areas and reserves.

For these reasons, among others, macroeconomic models must be tailored to "play well" with environmental analyses. They must respect the physical realities that govern resource extraction, protection, distribution, and use. They must also acknowledge the ways in which prices are set, a topic explored at greater length below. Concretely, this usually means some degree of sectoral disaggregation and attention to the multiple ways in which prices are set for resources and resource-dependent goods and services.

4 Models in use today

This section introduces a few of the top-down, bottom-up, and hybrid models currently in use for analyzing water, energy, and related sectors and resources in policy applications.

4.1 Top-down models

While most energy-economy models are bottom-up, starting with a physical representation of the energy system (Nikas, Doukas, and Papandreou 2019, 30 ff.), top-down models that start with a representation of the economy are also used. Of those, CGE models are the most common, particularly for energy (Hourcade et al. 2006, 2), although input-output models are a common choice for water-economy models as well (Bekchanov et al. 2017). Wing (2011) provides a detailed methodological introduction to CGE models for energy and environmental analysis, albeit while repeating common misconceptions about the origins and theoretical heritage of CGE models (see Mitra-Kahn 2008). Development of water-economy models began more recently than energy-economy models, but they have multiplied rapidly and several are of the CGE type (Bekchanov et al. 2017; Briand et al. 2023, 261–62).

For purposes of exposition, two prominent and related models provide a useful reference: GTAP-E for energy (Burniaux and Truong 2002; McDougall and Golub 2009; Peters 2016) and GTAP-W for water (Berrittella et al. 2007; Calzadilla, Rehdanz, and Tol 2011). Both are based on the widely-used model of the Global Trade Analysis Project (GTAP) hosted at Perdue University;[6] indeed, GTAP-W was an extension to GTAP-E (Berrittella et al. 2007, 1801). Both models have undergone improvements over time. They introduce natural resources by extending the nested production structure built into GTAP.

As with nearly all CGE models, GTAP is closed by setting prices to clear markets. For this reason, resource use in GTAP-E and GTAP-W is mediated by prices. The interest in price responsiveness was, for energy models, a response to the 1970s oil crisis. Prior to that date, energy prices were comparatively steady, and energy models considered only the impact of economic growth – an exogenous assumption –

[4] Thermal power plants are those that heat water to generate steam to drive a turbine, which generates electricity. They include coal, oil, and nuclear plants. Modern natural gas plants drive the turbine with the combusted gas, hydropower plants drive the turbine with water falling from a higher to a lower elevation, and wind plants drive the turbine by means of a rotor driven by wind passing over the wind tower's blades. Solar plants do not require a turbine.
[5] E.g., see https://www.epa.gov/indoor-air-quality-iaq/sources-combustion-products.
[6] https://www.gtap.agecon.purdue.edu/.

on energy demand (Manne, Richels, and Weyant 1979). The energy crises shifted the analytical focus to the impact of rising energy prices on economic output, inflation, and employment (Hamilton 1983). Following standard neoclassical theory, models sought to understand price-induced complementarity and substitutability of inputs. Processes included inter-fuel substitution (e.g., replacing oil with natural gas) and, where possible, substitution between energy and capital (Burniaux and Truong 2002, sec. 3.2 & 3.3).

The GTAP-E developers justify their top-down approach with the aim of providing a "widely accessible" energy model (Burniaux and Truong 2002, 27). Their strategy is to provide an extension to an already widely-used economic model, GTAP; for GTAP users, this substantially reduces barriers to implementation. Energy is introduced in GTAP-E by extending GTAP's nested production function structure. Energy is separated into electricity and non-electricity; substitution occurs between non-electricity fuels and between electricity and the bundle of all other fuels as a whole, an approach followed in other models as well (see the literature reviews in Burniaux and Truong 2002; Peters 2016). The model then allows for substitution between capital and the electricity + non-electricity energy composite. With such a nested structure, even if capital and energy are complements, capital can be substitutable with respect to specific fuels (Burniaux and Truong 2002, 30).

Most water-economy modeling exercises focus on water constraints (e.g., Freire González 2011; Ortuzar, Serrano, and Xabadia 2023). That is true of GTAP-W as well. The GTAP-W modeling team developed a set of satellite water accounts for GTAP, calculating physically-based "water intensity coefficients," or the water required to produce one unit of a commodity. GTAP-W simulates the absolute physical constraint on water by treating water supply as inelastic. Rationing occurs through a price mechanism, giving rise to rents associated with water resources. The water intensity coefficients then change in response to water prices.

4.2 Bottom-up models

Bottom-up environment-economy models begin with a (bio-)physical (or "engineering") environmental model and then add an economic model to it. A prominent example for energy-environmental analysis is the sequence of models that began with ETA-MACRO and then passed through MARKAL-MACRO, MESSAGE-MACRO, TIMES-MACRO, and MERGE (Manne 1977; Manne and Wene 1992; Messner and Schrattenholzer 2000; Manne and Richels 2005; Loulou, Goldstein, et al. 2016; Loulou, Lehtilä, et al. 2016). Since it was first implemented as an extension to the physical energy model ETA, the macroeconomic model MACRO has undergone some significant changes, but has remained a one-sector model with a CES production function that includes capital, labor, and energy; maximization of the discounted sum of log consumption net of energy costs to determine an optimal investment pathway; and investment expenditure spread over time, so that physical capital can lag investment expenditure by several years. MACRO is an optional add-on to the widely-used TIMES energy model, which is a detailed bottom-up partial equilibrium model of the energy sector that mixes physical and monetary accounts.

Bottom-up water models tend not to be whole-economy models (Harou et al. 2009; Bekchanov et al. 2017). They are often called "hydro-economic" models, although the term is also loosely used to mean any water-economy model, even top-down CGE models with limited disaggregation of the water sector. One (partial) exception, a model by Jonkman et al. (2008) adds an input-output model to a physically-based and detailed hydrological model. The goal is to understand indirect impacts of flood damage. However, the economic model is not dynamic, and does not feature feedbacks to the water model.

4.3 Hybrid models

Hybrid models combine features of both bottom-up and top-down models. A key example is Cambridge Econometrics' E3ME family of models (Pollitt, Chewpreecha, and Summerton 2007; Mercure et al. 2018). From the start, the set of models were built to simulate Energy-Economy-Environment interactions (hence "E3"), and they did so by combining physical energy and environmental models with a macroeconometric model. The most recent version includes technology transition sub-models for power (electricity), transport, agriculture and heating using the Future Technology Transformations (FTT) modeling approach (Mercure 2012). It also includes two biophysically-based models: a detailed land productivity model (LPJmL) and a climate model (GENIE 1) (Mercure et al. 2018, fig. 1).

The E3ME model is characterized by its creators as post-Keynesian.[7] The model assumes fundamental uncertainty about the future and is driven by effective demand. It features wage bargaining, potential underutilization of capacity, Schumpeterian finance (Pollitt and Mercure 2018), and out-of-equilibrium dynamics (through error-correction models). It is a highly disaggregated global model that has been applied to practical policy analysis in a variety of contexts.

For water-economy modeling, most hybrid models, as the term is used in this paper, are combined physical-CGE models. In the water-economy literature, "hybrid" is often used to mean a mix of optimization and simulation. One paper that uses the term in the sense of combining a bottom-up engineering model with a top-down economic model is the study of the Grand Ethiopian Renaissance Dam by Kahsay et al. (2019). However, the flow is one-way, from the engineering-based partial equilibrium model to the GTAP-W CGE model, without subsequent feedback.

4.4 Critical reflections

Referring back to the "general considerations" in Section 3, existing top-down and hybrid models do well on one important criterion: they are multi-sectoral. Furthermore, all types of models – top-down, bottom-up, and hybrid – include resource substitution and technological change, and treat investment as occurring in historical time, with lags between expenditure and availability of physical capital. Morevoer, bottom-up and hybrid models often do well at representing the geographic specificity of resources. Thus, taken as a whole, the suite of existing models addresses most of the criteria, with hybrid models performing best.

The main problem with existing top-down models is that the market-clearing price mechanism they employ does not "play well" with environmental analysis. In neoclassical environment-economy models, consumers and producers are typically treated as "price takers" that maximize their utility (for consumers) or profits (for producers) at given prices. However, prices nevertheless do change in the models in order to clear the domestic market. This is a standard feature of neoclassical models, but as with any such model, it is unclear by what agency the price change occurs, since no agent in the model has the power to do so (Fisher 1983, 12).

What is more, it is well-known who sets prices in many energy and water markets. In the 1980s, when rising oil prices drove the change in focus in energy modeling towards price-induced substitution, end-use energy markets around the world were substantially regulated (Samouilidis and Mitropoulos 1982). They were subsequently deregulated in some high-income countries, but Boyd (2020) argues that the deregulated markets are not well described by purely competitive models. In low- and middle-income countries, consumer energy prices continue to be regulated (Jamasb 2006), driven by concerns over affordability (Fankhauser and Tepic 2007; Winkler et al. 2011) and social acceptability (Williams and

[7] https://www.e3me.com/features/approach/

Ghanadan 2006). Water markets continue to be strongly regulated nearly everywhere. This puts the main adjustment mechanism for these models – market-clearing prices – in question.

A further problem shared by MARKAL-TIMES and GTAP is that they rely on aggregate production functions, which are known not to exist (Fisher 1969; Felipe and McCombie 2013; Harcourt, Cohen, and Mata 2022). This critique is well-known to post-Keynesians and will not be rehearsed here.

5 Notes from the field

Sustainability and resource planning by national and sub-national governments has created a demand for environmental-economic modeling. The demand has been met primarily by adapting pre-existing models. Three examples were provided above: extending CGE models in a top-down fashion, exemplified by GTAP-E and GTAP-W; adding a comparatively thin macroeconomic layer on top of detailed physical models, exemplified by MARKAL-MACRO; and combining detailed physical models with a modified version of an existing economic model, exemplified by E3ME.

5.1 The AMES model

The author has built several models to respond to issues raised by partners in low- and middle-income countries. Most are project-specific, but one, the Adaptable Macroeconomic Extension for Sustainability analysis (AMES) is a general model that is being applied in multiple projects (Kemp-Benedict forthcoming).[8] AMES is an relatively new open-source model that is designed to work together with the Low Emissions Analysis Platform (LEAP), a widely-used physically-based energy modeling platform that has been in development for over two decades.[9] AMES supports links to other models as well. These additional features are being used by the author to link AMES and LEAP together with the Water Evaluation And Planning (WEAP) water and land-use planning and modeling platform.[10]

AMES is a multi-sector post-Keynesian (structuralist) macroeconomic model. Domestic prices in AMES are set as a markup on costs, while wages are determined by a simplified conflict-based model. AMES can be run independently, but is not designed as an economic policy model. Rather, it is designed to provide economic drivers to LEAP and other models, and to accept physically-based drivers from LEAP and other models. In particular, public energy investment in LEAP adds to investment as simulated in AMES using an investment function. The author is currently implementing a link to WEAP by passing crop production and sectoral water constraints from WEAP to AMES.

The design strategy for AMES is to rely as much as possible to the physically-based models while ensuring consistency at the whole-economy level. Because the economic accounts in AMES are closed by quantity adjustment in each year, while prices change between years, linking to physically-based models is reasonably straightforward. It is much more challenging to follow the currently dominant approach of linking physical and economic models when price adjustment is used to close the economic model; fortunately, quantity and not price adjustment appears to rule in reality.

Building a dynamic multi-sector model raises both opportunities and challenges. Prices must be tracked by sector, and the structure of production can change due to changing demand patterns, technology, and trade. The author followed both the post-Keynesian and Sraffian literature, adding to the literature where there are gaps, particularly around technological change (Kemp-Benedict 2019; 2022).

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[8] The AMES model is thoroughly documented online: https://sei-international.github.io/AMES.jl/stable/.
[9] See: https://leap.sei.org/.
[10] See: https://weap.sei.org/.

5.2 General observations

Building environment-economy models requires cross-disciplinary collaboration. In the author's experience, most energy and water experts have been taught elements of neoclassical micro-theory, but are strongly grounded in the physical reality of the resources and systems that they study. What they look for in an economic model is plausibility and relevance, and they do not much care about schools of thought. They are happier with bottom-up and hybrid models than they are with top-down models.

Similarly, analysts in planning agencies are interested in plausibility and relevance. For them, relevance means both that the model provides variables of interest – particularly employment, growth, and trade – and accepts inputs that coincide with proposed initiatives in national, regional, and sectoral plans.

Plausibility and relevance are the key goals of structuralist analysis in the tradition of Taylor (2004) (Gibson 2003). They therefore offer promising entry points for economists working in post-Keynesian and Sraffian traditions. However, policy audiences also demand credibility from their models, and that can be a stumbling block.

Credibility is conferred in at least three different, sometimes competing, ways: longevity, authority, and goodness-of-fit. Of these, longevity is most desirable, because it requires the least evaluation by the potential model user. That is why GTAP-based models, the descendants of ETA-MACRO, and E3ME are so widely used. For models with a shorter history, authority is best. This could be because of the prominence of the model developer (a Nobel Memorial Prize helps) or because it aligns with prevailing economic convention. Both of these criteria are problematic for non-neoclassical models, with the exception of E3ME.

Failing the first two criteria, goodness-of-fit remains. CGE models either do poorly on this count, or they do not even attempt to perform well, as they are often "calibrated" to a single reference year. This provides an opening for alternative approaches.

A further consideration for potential model users – although subordinate to plausibility, relevance, and credibility – is accessibility. Many planning agencies, particularly in low- and middle-income countries, wish to develop their own in-house capacity. That is the main reason that AMES is an open-source model (the other is transparency). It is worth noting that many of the integrated assessment models used for climate policy are open source as well, although they were not the focus of this paper. In contrast, the models reviewed in this paper are not free of charge and can be quite costly. Users must purchase a license to and MARKAL-TIMES, but they then usually run the model themselves. E3ME is available for license but the developers strongly urge potential users to hire the E3ME team to run the model.

6 Conclusion

There is a demand for environmental-economic models for policy analysis. Potential users are overwhelmingly pragmatic, and will evaluate models for their plausibility, relevance, credibility, and (if the others are satisfied), accessibility. This provides ample opportunity for models based on post-Keynesian, Sraffian, and related traditions.

Nevertheless, the road is steep and strewn with obstacles. Many of the obstacles arise from the practicalities of linking physical and economic models: environment-economy models must respect the physical reality of natural resources, must nearly always be multi-sector, and must perform well when compared to historical data. Other obstacles arise from the need to establish credibility. Without invoking doctrinal disputes, which leave policy audiences cold, anyone providing a new non-neoclassical model must overcome the drawbacks of newness and unconventionality. The best remaining argument is model performance.

While building practical policy models is hard, it is made easier if suitable model components are ready to hand. Post-Keynesian theory offers considerable insight into the determination of prices, investment, wages, interest rates, and other key variables. Sraffian theory has much to say about price formation in a multi-sector setting, as well as the structural impact of changing demand and technology. Nevertheless, theory remains somewhat thin when it comes to specific resources and other environmental concerns.

The literature on energy-economy and water-economy models, which is dominated by neoclassical models, grapples earnestly with the problems inherent in linking physical and economic models. While post-Keynesians and Sraffians may reject the economic assumptions, the problems described in that literature remain to be solved. It provides a rich resource, spread through specialist energy and water journals, for clues and guides to areas where post-Keynesian, Sraffian, and related theory can be further developed.

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