AMES: A model for energy, economic and environmental assessment

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Abstract

This paper introduces the Adaptable Macroeconomic Extension for Sustainability analysis (AMES). AMES is a multi-sector, demand-led, structuralist model designed to provide consistent economic drivers to the widely used Low Emissions Analysis Platform (LEAP). The focus is on low-emission development strategies in low- and middle-income countries. Together, LEAP and AMES form a hybrid energy-economy model that combines two approaches: bottom-up energy-systems analysis and top-down macroeconometric assessments. Because of its focus on low- and middle-income countries, AMES can simulate structural change. Moreover, unlike most macroeconomic models used for energy analysis, AMES exhibits hysteresis, in which, for example, an energy investment programme can lead to persistent, positive impacts on GDP and employment. An open-source tool hosted on GitHub, AMES is a flexible model designed to be adapted for specific needs and studies.

Keywords: LEAP; NEMO; low emission; low income; middle income; macroeconometric

1. Introduction

Many low- and middle-income countries are preparing low-emission development strategies, defined as “national, subnational or supranational strategies for achieving low-emission long-term (often focused at mid-century) development considering broader sustainability, socioeconomic and climate change adaptation goals” (Rocha & Falduto, 2019). As this characterization underscores, the goals of these strategies are broader than emissions reductions *per se*.

Indeed, these strategies can both contribute to and relieve many challenges faced by low- and middle-income countries. For example, transformation of the energy sector can entail a short-run impact on the trade balance through capital goods imports, even as switching from fossil imports to domestic renewable energy production can improve the trade balance in the longer run. Strategies can produce a positive short-run impact on employment and income because a building boom requires construction workers, who are usually local; yet, over the longer run, if domestic energy costs rise, strategies can negatively impact profits or competitiveness across the economy.

Analytical tools have been devised to generate low-emission scenarios (e.g., Kousksou et al., 2015; Mondal et al., 2018; Grottera et al., 2020; Correa-Laguna et al., 2021; Handayani et al., 2022; Heaps, 2022; Wambui et al., 2022), but analysing these strategies to inform regional and national policy planning requires approaches that combine modelling to address energy, the economy and the interaction between the two.

Such combined energy-economy modelling expanded rapidly in the US following the 1970s oil crisis (Manne et al., 1979), which brought attention to the negative impacts of rising prices on economic output and employment (Hamilton, 1983). The goal at that time was to understand how energy prices affected economic activity and vice versa. These models assumed competitive markets, but in the 1980s, most energy markets were substantially regulated (Samouilidis & Mitropoulos, 1982). While they were subsequently deregulated in some high-income countries, in practice, government price-setting shifted to “price-making” practices strongly influenced by private interests, with results that departed from the competitive ideal (Boyd, 2020). Moreover, energy markets continue to be heavily regulated in low- and middle-income countries (Jamasb, 2006).

Accompanying the assumption of competitive markets, most energy-economy models focus on price-based mechanisms and policy instruments. This fails to capture barriers to transformation beyond costs (Worrell et al., 2004; Gillingham et al., 2009). While this holds true for countries at all income levels, once barriers are admitted, it is important to note that the barriers for developing countries differ from those of historically industrialized economies (Pandey, 2002, p. 102). Hurdles include limited capabilities of the existing capital stock, trade barriers, inadequate support for research and development, and limited resources for training and technological upgrading. Additional structural factors include the rural-urban divide, inappropriate subsidies, and a large informal sector (Urban et al., 2007). In the energy sector, developing countries seek equity of access and sustainable resource use even as they work to rapidly expand energy access in a fluid policy environment (Pandey, 2002, p. 98). The implication is that an appropriate energy-economy model for a developing country will likely differ from that for a high-income country.

Against this backdrop, this paper presents a new energy-economy model, the Adaptable Macroeconomic Extension for Sustainability analysis (AMES),[1] which was developed specifically to support low-emission development planning in ways that incorporate conditions relevant situations faced by low- and middle-income countries. While AMES can be run by itself, it is fully integrated with the Low Emissions Analysis Platform (LEAP) (Heaps, 2016). The construction of AMES follows structuralist theory by foregrounding quantity adjustment in response to demand,

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[1] The Low Emissions Analysis Platform (LEAP) is a platform for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute (https://leap.sei.org). AMES is an open-source extension to LEAP, written in the Julia scripting language with the JuMP mathematical programming sub-language. It is available on GitHub (https://github.com/sei-international/AMES.jl), including documentation (https://sei-international.github.io/AMES.jl/stable/).

with price adjustment as a secondary mechanism (L. Taylor, 2004b, Chapter 5). The LEAP model balances supply and demand for energy, while the AMES model balances supply and demand in all other sectors. LEAP provides time series based on a physical-energy model to AMES, while AMES provides time series of economic variables to LEAP. A consistent solution is found by iterating the integrated LEAP-AMES system to convergence.

The structure of this paper is as follows: Section 2 explains the purpose of the AMES model and contrasts it with the TIMES-MACRO model. Section 3 explains the design of the model, cross-referencing to the extensive online documentation. Section 4 shares outputs from the sample model distributed with the AMES package. Section 5 lists some features that extend the core AMES model; Section 6 concludes.

2. Model purpose

Contemporary debates on energy-economy modelling centre on the distinction between top-down, bottom-up, and hybrid energy-economy models (Hourcade et al., 2006). Top-down models emphasize economic factors and are typically, but not always, implemented as computable general equilibrium (CGE) models. Bottom-up models, by contrast, emphasize technological factors. Hybrid models seek to harness the strengths of each approach. AMES, when implemented as an extension of LEAP, is a hybrid that combines a top-down macroeconomic model with a bottom-up energy modelling platform.

AMES is an example of a macroeconometric model (Nikas et al., 2019). In contrast to CGE models, which typically assume that the economy is at full capacity, with the possible exception of the labour market, macroeconometric models such as E3ME (Cambridge Econometrics, 2014; Hourcade et al., 2006, p. 6; Mercure et al., 2018) and AMES allow for the economy to operate at less than full capacity. In such models, pursuing climate policies can stimulate the economy, leading to higher employment and output. CGE models, by contrast, tend to simulate higher costs and crowding out of private investment (Nikas et al., 2019, pp. 37–38).[2]

When fitting LEAP into classification schemes that have appeared in the literature, the classification should take into account LEAP combined with the optimization extension NEMO (the Next Energy Modeling system for Optimization).[3] NEMO is new enough that surveys of energy models do not yet include it. However, the creators of NEMO started by reproducing the features of the Open Source Energy Modelling System (OSeMOSYS), and LEAP and OSeMOSYS are included in at least two reviews: by Ringkjøb et al. (2018) and by Prina et al. (2020). According to those reviews, the combined features of LEAP and OSeMOSYS are very similar to those of MARKAL/TIMES. For that reason, the most comparable model in the MARKAL/TIMES family, TIMES-MACRO, will be used for comparison to LEAP, combined with both AMES and NEMO, later in this section. As TIMES-MACRO is an optimizing model, and not a CGE, AMES will sometimes also be compared to CGE models throughout the paper.

It is worth noting some misconceptions about the nature of CGE models. While often presented as a special case of applied general-equilibrium models, which emerged from the neo-Walrasian tradition of Arrow and Debreu (e.g., as in Wing, 2011), CGE models stand in a different tradition, stemming from the work of Johansen (1960), to Taylor and his co-authors (L. Taylor & Black, 1974; L. Taylor & Lysy, 1979), to Adelman and Robinson (1978). As argued by Mitra-Kahn (2008), CGE models are built around macroeconomic balances in the form of social accounting matrices rather than excess demand functions as in general equilibrium theory. Crucially, the "equilibrium" in a

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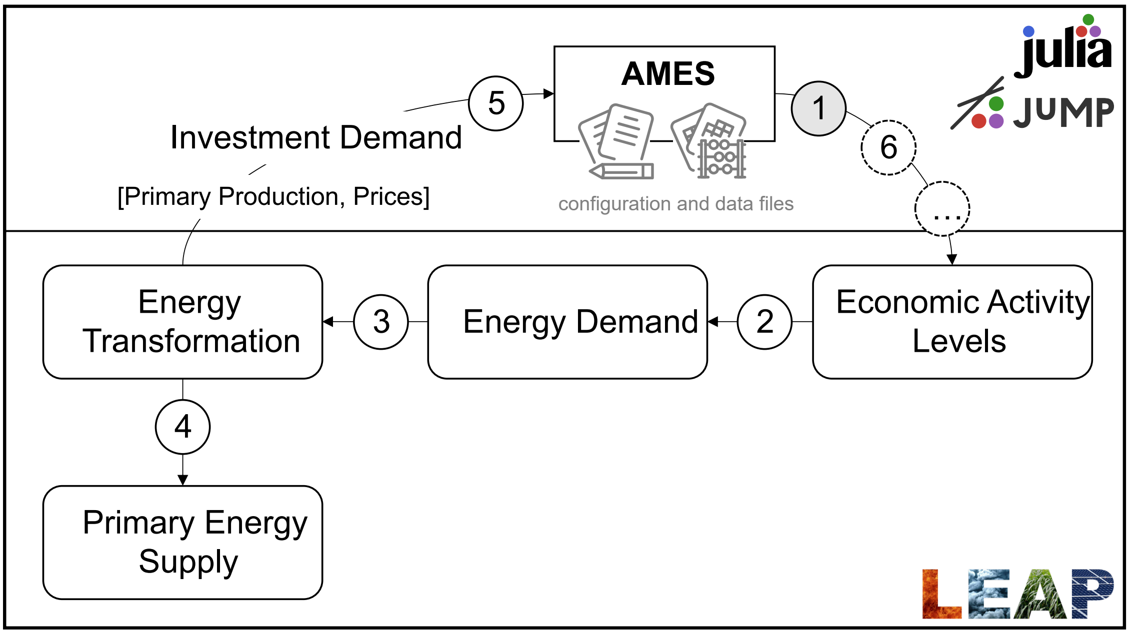
[2] One caveat is that while CGE models for energy analysis tend to follow a common template, macroeconometric models encompass a variety of approaches, so the AMES model is quite different from, for example, E3ME.

[3] Like AMES, NEMO is an open-source program written in Julia with JuMP and hosted on GitHub (https://github.com/sei-international/NemoMod.jl).

Figure 1. AMES interface and iterative solution



CGE is not a dynamic equilibrium; rather, it is an accounting identity. The way in which the identity is achieved is the model "closure." While most CGE models today are closed by adjusting prices, comparing alternative closures can be enlightening (L. Taylor & von Arnim, 2007). The AMES model described in this paper is similar in spirit, although not in its details, to structuralist CGE models (L. Taylor, 1990b).

2.1 Purpose of the AMES model

The AMES model aims to provide consistent economic drivers to LEAP in the form of GDP, sectoral output (or value added), and (optionally) employment. In a typical LEAP application, economic drivers are exogenous. However, if a low-emission development strategy requires public investment in energy infrastructure, the investment expenditure would impact the rest of the economy, calling the external drivers into question. The AMES model incorporates investment expenditure with other LEAP outputs, adjusts its calculation of economic drivers, and passes them back to LEAP. The integrated LEAP-AMES system is solved iteratively to a user-specified tolerance, as illustrated in Figure 1.

The goal of providing consistent economic drivers to LEAP drives some key design decisions for AMES (as detailed in Section 3). While AMES can be run both on its own and separately from LEAP, it is not intended for economic policy analysis. Rather, it is designed to be combined with LEAP to supply economic feedbacks to a detailed energy model for a linked energy-economy analysis.

The AMES model has several additional design goals. Among the most important is that it should answer the planning needs of low- and middle-income countries seeking to create development strategies that lower their greenhouse gas emissions.[4] This broad goal lies behind many of the specific design choices and motivates an overarching design goal of flexibility to address specific national needs (e.g., see Waisman et al., 2019).

A further design goal is that AMES should support sustainability planning, suggesting a multi-sector structure. Further, in low- and middle-income countries, structural change is a major

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[4] This aligns with the goals of LEAP; see https://leap.sei.org/default.asp?action=introduction.

consideration that motivates sector-specific strategies (Urban et al., 2007). For this reason, the AMES model requires a set of supply-use tables (SUT), although it can also accept a symmetric input-output table if supply and use tables are not reported separately. This may appear to be a forbidding requirement in data-scarce environments. However, CGE models also require sectoral detail, in the form of a social accounting matrix, in which SUT are embedded. Because of the popularity of CGE models, a few international organizations, including the World Bank and the International Food Policy Research Institute (IFPRI), have supported a large number of countries to prepare these social accounting matrices.[5]

2.2 Contrast with TIMES-MACRO

To clarify some of the design choices in AMES (with LEAP and NEMO), it is helpful to contrast with TIMES-MACRO. The integrated LEAP-NEMO-AMES system makes different choices than TIMES-MACRO while addressing very similar types of energy system planning questions. This section explains the different choices for potential users of either model. While the comparison entails critique of TIMES-MACRO, the critiques arise from competing approaches to economic analysis: neoclassical on one hand and structuralist on the other. TIMES-MACRO is a solidly built, neoclassical model; by contrast, AMES, we believe, is a solidly built, structuralist model. There are arguments for each approach, and users may choose the modelling system that best matches their understanding of the economy and energy system in their country.

The remainder of this section draws on several sources, which are cited together here rather than in the body of the text: descriptions of the macroeconomic model MACRO as it evolved over time (Manne, 1977; Manne & Richels, 2005; Manne & Wene, 1992); and documentation for TIMES (Loulou, Goldstein, et al., 2016; Loulou, Lehtilä, et al., 2016). The focus will be on economic assumptions.

2.2.1 Macroeconomics: MACRO versus AMES

Throughout subsequent versions (e.g., ETA-MACRO, MARKAL-MACRO, and MERGE), MACRO has retained some key features: a one-sector economy with output determined by a nested constant elasticity of substitution function including capital, labour 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 to generate a lag between investment and the availability of physical capital. These features mark it as a neoclassical model grounded in welfare economics. Changes since ETA-MACRO include: a switch from final energy to energy services; addition of an autonomous energy efficiency improvement parameter; and incorporation of trade when implemented as a global multiregional model. (The national MACRO model remains closed to trade.)[6]

In contrast, the AMES model is a multi-sector model in which production is determined by capacity utilization multiplied by potential output. Sectoral potential output is proportional to the capital stock, and demand for inputs, including labour, is proportional to production. Labour productivity and, optionally, input-output coefficients, adjust dynamically, producing endogenous technological change along broadly Kaldorian lines (Setterfield, 2013). Unlike in neoclassical models, in which substitution is instantaneous, in AMES costs and (for labour) investment rates determine productivity growth rates, which have a cumulative impact on productivity. Also unlike neoclassical models, prices are set as a markup on costs, an assumption with a solid empirical foundation (Coutts & Norman, 2013).

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[5] For example, in the IFPRI Dataverse: https://www.ifpri.org/publication/ifpri-dataverse.

[6] The version of MACRO that appears in MERGE makes a significant innovation not taken up in TIMES-MACRO, to simulate "putty-clay" investment dynamics by having the production function apply only to marginal changes in productive capacity.

The type of production model in AMES is sometimes referred to as a fixed-coefficient model.[7] However, while the coefficients are instantaneously fixed, they can change over time. That assumption fits the observation that in the short run firms have limited scope for substitution; most adjustment is through capacity utilization of existing capital (as observed in firm behavior; see Mattey & Strongin, 1997). Substitution plays out over time through a combination of embodied and disembodied technological change.

2.2.2 Energy: TIMES versus LEAP/NEMO

The counterpart to LEAP with NEMO is TIMES. For national studies, TIMES is a detailed bottom-up partial equilibrium economic model for the energy sector that keeps track of physical energy production and consumption together with prices. Consistent with the theoretical underpinnings of its MACRO companion, TIMES is a neoclassical model with competitive markets that incorporates ideas from welfare economics.

Over the long time horizon of a low-emission development strategy, changes in demand are driven more by income than price effects. Structural change is a dominant dynamic in low- and middle-income countries (Urban et al., 2007), and the classic study by Chenery, Robinson, and Syrquin (1986, Chapter 3) treats income effects, together with trade and technological change, as a key driver of structural change. TIMES accounts for this by constructing a reference level of demand D_0 determined by a user-specified function of economic drivers such as GDP. A typical LEAP exercise would calculate demands in a similar way, but TIMES goes further by calculating reference prices P_0 as the shadow price of that demand when maximizing the social surplus in a reference scenario. The user specifies a price elasticity of demand E, so demand in the model is $D = D_0(P/P_0)^E$.

In the TIMES model, consumers and producers are "price takers" that maximize their utility (for consumers) or profits (for producers) at given prices. However, prices nevertheless change 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, p. 12). Furthermore, it is quite clear who sets prices in many low- and middle-income countries: government bodies through tariff schedules (Jamasb, 2006; Samouilidis & Mitropoulos, 1982, pp. 230–231). The reality of tariffs raises a further issue with standard welfare economic arguments. The social surplus incorporates the spending and production patterns of all consumers and firms. But energy for low-income consumers is a necessity; the willingness of wealthy households to pay for energy offsets the inability of low-income consumers to pay higher prices. For this reason, affordability (Fankhauser & Tepic, 2007; Winkler et al., 2011) and social acceptability (Williams & Ghanadan, 2006) are pressing concerns when setting prices.

In contrast to the neoclassical vision of TIMES, the NEMO model takes the point of view of a government agency or public utility doing a capital-budgeting exercise across alternative investments. The least-cost alternative that meets the simulated demand is chosen. That said, NEMO, like TIMES in its default operation, departs from reality by assuming perfect foresight. However, LEAP is not intended as a pure simulation model. Rather, it is a planning model for exploring alternative future pathways for energy and emissions.

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[7] Fixed coefficient models are also sometimes said to feature a "Leontief" production function, but for AMES that is a misleading projection of neoclassical theory onto a non-neoclassical model. In neoclassical models, the partial derivatives of aggregate production functions determine factor payments, but that procedure founders on the fact that an aggregate measure of the capital stock cannot be constructed that will yield the price of capital by treating it as a factor (Fisher, 1965, 2005; Harcourt et al., 2022). For this reason, the AMES model, like E3ME, does not assume an aggregate production function.

3. Model design

The AMES model is thoroughly documented online,[8] and the code is open source.[9] The online documentation lists all model variables and equations and describes the format and content of the input and output files. This section motivates the model structure and presents the main calculations. The focus in this section is a “core” model (see further details on extensions to the core in Section 5).

In general, macroeconomic models can be defined in terms of three elements: a system of accounting relationships; a set of behavioural rules; and one or more closure rules to bring the accounts into balance after the behavioural rules have been applied. The accounts for the AMES model are based on supply-use tables. This is a conventional choice that is very similar to the social accounting matrix in a CGE model. Behavioural rules in AMES determine changes from one (annual) time step to the next in prices, productivity, investment, employment and other variables. The model is closed each time step by adjusting quantities using a linear goal programme (LGP). The LGP ensures that production stays within the capacity of installed capital while minimizing a weighted sum of deviations from goals for full capacity utilization, domestic supply of domestic demands, and export demand. Imports enter as a residual balancing term.

3.1 The LEAP-AMES link

Together, LEAP and AMES (optionally including NEMO) make up a hybrid energy-economy model. All hybrid models face the challenge of flexibly linking a highly detailed physical representation of the energy sector to a more aggregate macroeconomic model, and they manage the link in different ways. For example, the TIMES-MACRO model conveys total energy costs from TIMES to MACRO, which then treats the rest of the economy as a single sector.

AMES manages the challenge by making an approximation that allows for a partial analytical separation between “energy” and “non-energy” sectors in the economy. Energy sectors encompass energy supply, transformation and distribution, while non-energy sectors form the rest of the economy. The approximation derives from the observation that the energy sectors contribute a small share of value added in most countries. This is because household expenses, which are covered by wages and salaries, include energy, food, housing, clothing and other costs. Moreover, energy costs cannot be too high a fraction of the total because households must first ensure their other costs are met. This makes wages a large multiple of energy costs. Firms, meanwhile, must cover labour and energy costs while generating a profit. Wages are typically the largest component of firm costs, so prices are also a large multiple of energy costs. Together, these multipliers keep energy costs as a share of GDP relatively low in most countries.

Despite its generally small contribution to value added, the energy sector has a disproportionate effect on the economy. When energy prices rise, they raise the cost of living and the cost of production across all households and sectors simultaneously. What is more, in industrializing countries, non-traditional final energy demand grows faster than the economy as a whole (Samouilidis & Berahas, 1983), so rising energy costs can be a brake on development. Hence, the energy sector cannot and should not be excluded. Nevertheless, it can be partly decoupled from the rest of the economy because, with energy value added typically small, purchases by the energy sector of goods and services from the rest of the economy are also typically small.

A different way to make the same point is that for most countries the energy sector mainly provides inputs to the rest of the economy. That is, it has high “forward linkages” (Hirschman, 1958; Cahen-Fourot et al., 2020). But at the same time, the energy sector typically has low

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[8] Documentation for the version described in this paper can be found at: https://sei-international.github.io/AMES.jl/v2.3.1/. For the most up-to-date production version, see: https://sei-international.github.io/AMES.jl/stable/. For the current development version, see: https://sei-international.github.io/AMES.jl/dev/.

[9] Available from https://github.com/sei-international/AMES.jl.

“backward linkages”, meaning that the supply of intermediate non-energy goods and services to the energy sector is comparatively small. There are cases in which the assumption does not hold; for example, a country that is a significant oil exporter might have a strong domestic demand from the oil sector for professional services and manufactured parts (see Section 5.1 for a discussion of extensions to the core AMES model).

The arguments above can be given more formal content. While the AMES model uses SUTs, the argument is clearer when put in terms of a symmetric input-output (I-O) table (e.g., see Eurostat, 2008, p. 349). The Leontief (1966) system can be written as a block-matrix equation split between energy (E) and non-energy (N) sectors,

$$\begin{pmatrix}\mathbf{Y}_E\\ \mathbf{Y}_N\end{pmatrix}=\begin{pmatrix}\mathbf{A}_{EE} & \mathbf{A}_{EN}\\ \mathbf{A}_{NE} & \mathbf{A}_{NN}\end{pmatrix}\begin{pmatrix}\mathbf{Y}_E\\ \mathbf{Y}_N\end{pmatrix}+\begin{pmatrix}\mathbf{F}_E\\ \mathbf{F}_N\end{pmatrix}+\begin{pmatrix}0\\ \mathbf{I}_N\end{pmatrix}+\begin{pmatrix}\mathbf{X}_E\\ \mathbf{X}_N\end{pmatrix} \tag{1}$$

In this equation, $\mathbf{X}$ is the vector of net exports, $\mathbf{F}$ is the vector of final household demand, and $\mathbf{I}$ is the demand for investment goods. Note that the subscripts on $\mathbf{F}$, $\mathbf{I}$ and $\mathbf{X}$ indicate the source of supply rather than demand. Hence, the entry $\mathbf{I}_E$ is set to zero because, while the energy sector contributes to demand for investment goods, it does not supply them.

3.1.1 The energy and economic subsystems

The energy and economic analyses are separated through the approximation motivated above, in which demand for non-energy goods from the energy sector is neglected (aside from investment goods). That is, $\mathbf{A}_{NE}$ is assumed to be comparatively small. Setting non-energy demand from the energy sector to zero as an approximation considerably simplifies the analysis. Equation (1) can now be written as two equations,

$$\mathbf{Y}_E=\begin{pmatrix}\mathbf{A}_{EE} & \mathbf{A}_{EN}\end{pmatrix}\begin{pmatrix}\mathbf{Y}_E\\ \mathbf{Y}_N\end{pmatrix}+\mathbf{F}_E+\mathbf{X}_E \tag{2}$$

and

$$\mathbf{Y}_N\cong\mathbf{A}_{NN}\cdot\mathbf{Y}_N+\mathbf{F}_N+\mathbf{I}_N+\mathbf{X}_N \tag{3}$$

Equation (2) is what LEAP evaluates: the energy supply needed to meet demand from the energy system itself, final household demand, exports and non-energy sectors. Equation (3) is a standard input-output calculation for the non-energy sector, and is solved by the Leontief inverse,

$$\mathbf{Y}_N=\left(\mathbf{1}_N-\mathbf{A}_{NN}\right)^{-1}\cdot\left(\mathbf{F}_N+\mathbf{I}_N+\mathbf{X}_N\right) \tag{4}$$

where $\mathbf{1}_N$ is the identity matrix for the non-energy sector. Despite the separation, the two submodels remain linked in two ways: 1) investment in the energy sector drives economic activity through a (dynamic) multiplier; and 2) activity drives energy demand.

Given a specification for final household demand, net exports and technical coefficients, Equation (2) determines output from the non-energy sector. That provides an input to LEAP. The flow of calculations (shown in Figure 1) is as follows: 1) the AMES model is run without LEAP outputs and produces time series for economic activity levels that are passed to LEAP; 2) LEAP uses the outputs from the AMES model to calculate energy demands; 3) those demands drive energy supply, including an estimate of the need for additional investment in the energy sector; 4) demand for primary energy is calculated within LEAP; 5) investment demand is then passed to the AMES model; and 6) the AMES model is run again. The combined models are run in an iterative fashion until the results show little change from one run to the next, as set by a user-specified tolerance. In practice, two to three iterations are usually sufficient.

3.1.2 Assessing the validity of the approximation

To measure how significant non-energy supply to the energy sector is for the economy, the following calculation is carried out within the AMES model. First, the Leontief inverse for the full matrix, $\mathbf{L}^{\text{full}}$, is evaluated,[10]

$$\mathbf{L}^{\text{full}} = \left[\begin{pmatrix} \mathbf{1}_{EE} & \mathbf{0} \\ \mathbf{0} & \mathbf{1}_{NN} \end{pmatrix} - \begin{pmatrix} \mathbf{A}_{EE} & \mathbf{A}_{EN} \\ \mathbf{A}_{NE} & \mathbf{A}_{NN} \end{pmatrix}\right]^{-1} \tag{5}$$

Second, the Leontief matrix $\mathbf{L}^{\text{reduced}}$ for a “reduced” matrix with $\mathbf{A}_{NE}$ set to zero is calculated,

$$\mathbf{L}^{\text{reduced}} = \left[\begin{pmatrix} \mathbf{1}_{EE} & \mathbf{0} \\ \mathbf{0} & \mathbf{1}_{NN} \end{pmatrix} - \begin{pmatrix} \mathbf{A}_{EE} & \mathbf{A}_{EN} \\ \mathbf{0} & \mathbf{A}_{NN} \end{pmatrix}\right]^{-1} \tag{6}$$

Finally, a metric, denoted R, is defined as

$$R = 1 - \frac{\sum_{i=1}^{n_s} \sum_{j=1}^{n_s} L_{ij}^{\text{reduced}}}{\sum_{i=1}^{n_s} \sum_{j=1}^{n_s} L_{ij}^{\text{full}}} \tag{7}$$

This metric is the relative change in total output when the reduced matrix is used rather than the full matrix under a change in final demand where demand changes by the same amount in all sectors. It therefore provides an order-of-magnitude estimate of the impact on economic output of neglecting the use of non-energy intermediate products by the energy sector.

When one interprets the metric it is important to recall that it is a variation applied to a variation. For example, suppose the value of the metric is R = 5%. Further, assume that peak deviation of GDP from a baseline scenario to a LEDS scenario is also 5%. Then excluding demand for non-energy goods and services by the energy sector could lead to a 5% adjustment of a 5% deviation, for an expected ±0.25% difference in GDP. That may quite reasonably lie within the range of uncertainty due to plausible variations in other model parameters.

3.2 Representing non-energy sectors

The AMES model is demand-led: the economy grows because firms make investments (a source of demand in itself) in anticipation of demand from households, for exports and for investment goods. In the structuralist tradition (Ocampo et al., 2009; L. Taylor, 1989, 2004b), the model balances its accounts through capital utilization, which is typically underutilized to maintain spare capacity. This assumption should be familiar to energy systems modellers, whose “capacity factor” corresponds to the structuralist economist’s “capacity utilization.” As a result of these and other interdependent dynamics, the economy in AMES follows a continually adjusting path that typically exhibits unbalanced growth.

The theoretical orientation of the AMES model contrasts with the neoclassical assumption that all factors of production are fully utilized, and prices rather than quantities adjust to bring accounts into balance.[11] Though structuralist models allow for price changes, prices in them do not clear markets. Rather, firms set prices as a markup on costs. They change prices rarely, and mainly in response to changes in costs, in line with empirical observation (Blinder, 1998; Coutts & Norman, 2013). When prices are set by markup, price adjustment tends towards unique and stable equilibria, although due to other dynamics the economy may never sit at the equilibrium (Kemp-Benedict, 2017).

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[10] In the AMES model, the “full” model is constructed by starting with the full set of accounts and then removing: 1) any sectors designated by the model user in a configuration file; 2) any sectors with zero production or products with negligible domestic production as determined by a user-specified threshold.

[11] Full utilization may not apply to labor in neoclassical energy-economy models in developing countries. In the standard neoclassical model, labor supply depends on the wage due to a leisure-labor tradeoff; everyone willing to work at the equilibrium wage is fully employed. However, in models for developing economies the competitive labor-market assumption is sometimes dropped in favor of an assumption that labor is under-utilized (e.g., Grottera et al., 2020, tbl. 1).

Rather than a smooth neoclassical production function, structuralist models assume instantaneously fixed-coefficient production structures. The coefficients may, however, change over time through technological change. The main mechanism assumed in structuralist models is the well-tested Kaldor-Verdoorn law, in which labour productivity growth is an increasing function of the investment rate (McCombie & Spreafico, 2016; Verdoorn, 1949, 2002). In line with the design goal of flexibility, the AMES model provides multiple options for specifying productivity growth. For labour productivity, models can either use the endogenous Kaldor-Verdoorn mechanism or specify productivity growth exogenously. AMES also offers a simplified version of a cost share-induced technological change mechanism for input-output coefficients (Kemp-Benedict, 2022).

The combination of mechanisms provided by AMES allows the model to simulate structural change. As noted by Urban et al. (2007), endogenous structural change is a needed but missing element in most energy models including, at the time of their review, LEAP.[12] AMES remedies this deficit. In keeping with Chenery et al. (1986), structural change in the AMES model can be driven by income effects (wage-dependent demand), trade (a further source of demand), and technological change. Moreover, structural change can be driven by costs. When labour demand rises faster than the working-age population, labour costs rise, temporarily reducing profits and discouraging investment. Changes in relative prices for goods and services can either raise or diminish profits and, if the cost share-induced technological change model is activated, can drive changes in input-output coefficients as well.

3.2.1 Supply-demand equilibrium

As noted earlier, supply-demand equilibrium is ensured for each time step (equal to one year) using an LGP.[13] Prices are fixed for this calculation. The objective function seeks to minimize deviations from a balanced condition in which demand expectations are precisely met. Goals are set for capacity utilization (full utilization), final household demand (maximum domestic coverage), exports (to reach potential external demand), and imports. Each high-level goal is given a weight, with the highest weight for utilization (user-specified, but defaulting to 8.0), the second for final demand (4.0), third for exports (2.0), and lowest for imports (1.0). The key adjusting variable is capacity utilization, which is set in each sector to minimize the distance from the goals.

Each goal (except the import goal) corresponds to common policy targets from the country's perspective: operating the economy at its full potential; meeting domestic needs from domestic production; and generating export revenue. By minimizing the weighted distance from the goals, the AMES model can be interpreted as having an optimistic bias; to the extent possible, policy targets that are often not met in practice are met in the model. This feature aligns with AMES's primary purpose, to provide consistent economic drivers to LEAP. It is also a reason why AMES is not suited for use in isolation as an economic policy model. While there are many flavours of economic policy analysis, a key question is to understand why certain economic goals might not be met, and therefore what needs to be remedied to meet them; AMES avoids the details necessary for such an analysis by simply assuming that the goals are met to the extent possible given production constraints.

In addition to the overall goal weight, separate weights are assigned for the first three goals for each sector. These capture the relative importance of certain goods in output, the export basket and final household demand. Sectors are uniformly weighted in the import target because import flexibility plays a residual balancing role in the model, allowing demand to be met when domestic production is insufficient.

Between solutions of the LGP the model updates productive capacity, wages and labour demand, domestic prices and final demand.[14] Productive capacity increases through investment, which adds to final demand.

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[12] LEAP and some other energy models allow for exogenously specified structural change.

[13] See https://sei-international.github.io/AMES.jl/v2.3.1/lgp/.

[14] See https://sei-international.github.io/AMES.jl/v2.3.1/dynamics/.

3.2.2 Investment

In AMES, an investment function determines the investment rate per unit of existing capital stock, net of depreciation. Structuralist models typically adopt post-Keynesian (neo-Kaleckian) formulations of the investment function (Lavoie, 2022; L. Taylor, 1990a, 2004b). Following standard neo-Kaleckian theory (Blecker, 2002) and empirics (Fazzari & Mott, 1986), investment rises with capacity utilization as firms respond to observed expansion in sales. Firms target a normal level of utilization. While the normal level can change over time (Nikiforos, 2013) and is influenced by a variety of factors (Corrado & Mattey, 1997; Goel & Nelson, 2020; Lecraw, 1978), we assume it to be fixed and normalize it by setting it equal to one.

Investment also responds positively to sector profit rates. The default option is to use realized profit rates at the level of capacity utilization. However, AMES offers as an option to use profit rates at normal capacity utilization along the lines proposed by Bhaduri and Marglin (1990, p. 380). The underlying assumption is that investors seek a target profit rate and will shift investments between sectors as profitability rises above or below the target. Divergent investment rates across different sectors drive structural change, as unprofitable sectors lose investment while profitable sectors attract additional investment, a key dynamic in the classical tradition (Pasinetti, 1981; Shaikh, 2016).

Investment is assumed to decline with the central bank's interest rate due to higher borrowing costs. This is a conventional assumption. It is also consistent with neo-Kaleckian theory, practice, and empirics (Lavoie, 1995). The AMES model implements a Taylor (1993) rule, in which the interest rate is equal to a target plus deviations depending on the departure of inflation and GDP growth from their target levels. The target interest rate itself can optionally depend on the nominal exchange rate (see Section 3).

Finally, investment rises with the net export-to-GDP ratio. When exports exceed imports, the country accumulates foreign exchange, easing repayment of foreign debt. When exports fall below imports, the country may be accumulating debt vis-à-vis the rest of the world, making repayment more challenging. Because investment goods are often imported, this mechanism tends to stabilize net exports.

Following standard practice, but largely dictated by data limitations, we assume a linear investment function. In the language of Hicks (1950), the intercept – defined as the investment rate when utilization, the profit rate and the central bank's interest rate are at their target levels and net exports are zero – is "autonomous investment". The response to the investment rate with changes in any of those variables is "induced" investment. Again following Hicks, we assume that firms never dismantle potentially productive fixed capital stocks, so gross investment never falls below zero and the (negative of) the depreciation rate sets a floor on the net investment rate. Despite its name, autonomous investment is endogenous in AMES: sectoral autonomous investment adjusts to observed growth through an adaptive expectations mechanism.

3.2.3 Prices, wages and interest rates

Five different sets of prices appear in the AMES model: world prices for traded goods and services; the exchange rate; domestic prices of goods and services; wages; and the central bank rate.

World prices for goods and services are set in international markets in which the country is presumed to be a price taker. The AMES model allows global price trends to be set exogenously for each product.

The exchange rate, either nominal or real, is presumed to be targeted by policy. A "fixed" exchange rate policy targets the nominal rate. For example, some tourism-dependent small island developing states fix their exchange rate relative to the currency of the main tourist source country (Inchausti-Sintes & Pérez-Granja, 2022). A fixed exchange rate policy may also be used to signal a commitment to keeping inflation under control (Hossain & Chowdhury, 1998, pp. 36–37). A “flexible” exchange rate may, at an extreme, be fully floating, but more often it is a managed float that seeks to accommodate a certain amount of inflation relative to other countries while maintaining a stable external balance (for example, via a ‘crawling peg’: see Connolly, 1985; Thornton, 2016).

A managed float that seeks to stabilize the external balance can be thought of as implicitly targeting the real exchange rate, which takes relative prices into account. The AMES model therefore allows either the nominal or real exchange rate to be specified exogenously. Any more general model is likely to be elusive; as noted by Taylor (2004a, p. 223), “the exchange rate…must evolve over time subject to rules based on expectations about its values in the future. In a world of shifting and perhaps unstable expectations, no simple dynamic theory is likely to emerge”.

Domestic prices are set as a markup on costs. There is a solid empirical basis for this assumption, as cost-based pricing is well documented in high-income manufacturing sectors (Coutts & Norman, 2013). Moreover, costing practices can now be ascertained in many developing countries using the World Bank’s Enterprise Surveys.[15]

In the AMES model, costs of intermediate goods and services use trade-weighted prices and therefore depend on the exchange rate. The markup, which is held fixed over time, is applied to “normal” costs; that is, costs at normal capacity utilization (a well-documented practice; see Coutts & Norman, 2013).

The real wage in AMES is anchored to, but not fully determined by, labour productivity. The real wage rises at the same rate as labour productivity when demand for labour grows at the (exogenous) growth rate of the working-age population. When demand for labour rises faster (slower) than the working-age population, the wage rises faster (slower) than labour productivity. Wages may be incompletely indexed to inflation, so nominal wage growth is set equal to real wage growth plus a user-specified fraction of the inflation rate (the inflation pass-through rate).

The central bank’s interest rate target on inflation and GDP growth follow a Taylor rule (as explained in Subsection 3.2.2). In AMES, the target can optionally depend on the nominal exchange rate. The direct effect of raising interest rates is an inflow of capital, which appreciates the domestic currency (Agénor & Montiel, 2015, p. 171). This can lead to persistently overvalued exchange rates combined with high interest rates (Bresser-Pereira, 2020). This mechanism suggests that interest rates and exchange rates move in opposite directions. However, inflation targeting by the central bank would lower interest rates when the exchange rate appreciates (Agénor & Montiel, 2015, p. 232 ff.). Thus, as a matter of policy, the target interest rate and the exchange rate should move in the same direction; however, that may not be possible (Agénor & Montiel, 2015, p. 234; Ocampo et al., 2009, Chapter 7). Given the uncertainties, the AMES model allows for the target interest rate to depend positively, negatively or not at all on the nominal exchange rate.

3.2.4 Final demand

Final demand for the country’s output in the AMES model consists of demand for investment goods and services, combined final household and government demand,[16] and demand for exports. Demand for investment goods is determined through the investment function, as explained in Subsection 3.2.2. Investment demand is always met and enters as a parameter rather than a variable in the LGP. For domestic final demand and exports, AMES calculates

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[15] Both aggregated and micro data are available from https://www.enterprisesurveys.org/en/enterprisesurveys. For example, in the 2017 Enterprise Survey for Colombia, by far the largest proportion of firms in most sectors that raised their prices did so because of changing costs. Competition was relevant only for the smaller number of firms that lowered their prices (80 lowered prices compared to 669 that raised them and 211 that kept them the same). Of the firms that changed their prices in either direction, 483 cited costs as a reason, 52 cited competition from domestic or foreign suppliers, 52 cited changes in demand, and 162 cited some other reason (or did not know the answer).

[16] Combining household and government final demand is an admittedly strong simplifying assumption, This a reason why AMES is not an economic-policy model. While a future version of AMES may loosen this assumption, it is retained for now because it greatly simplifies model construction.

a “normal” level of demand. The LGP includes a goal to minimize the difference between calculated and normal demand.

Following the standard post-Keynesian assumption that household demand is more responsive to changes in income than to prices (Lavoie, 2022, p. 123 ff.), the normal level for household demand responds to total real wages (the wage bill) through product-specific elasticities. Demand for different goods and services often exhibits strong variation in low- and middle-income countries as households change their consumption patterns with rising income. As the pattern is expected to change, the AMES model assumes that elasticities approach a steady value over time with a user-specified rate of convergence. Demand elasticities for user-specified “Engels products”, such as food, approach a user-specified elasticity less than one. Otherwise, when base-year elasticities exceed one (that is, when demand is elastic), the elasticities approach a value of one over time; elasticities less than one in the base year are maintained at their base-year values.

The normal level for exports increases with (exogenous) world GDP through product-specific elasticities, in line with balance-of-payments-constrained models (Thirlwall, 1979, 2011). It further depends on relative prices as the ratio of the growth factors for world and domestic prices to the power of a product-specific elasticity. The exogenously specified “world” growth rate may, indeed, be a global growth rate. However, it may also be a growth rate, such as an export share-weighted average growth rate, for trading partners; in such a case, the exchange rate should also be based on trading partners.

In the demand-led model presented in this paper, domestic household demand and demand for exports are the ultimate drivers of economic growth. Demand for investment goods follows from anticipated overall growth in demand and is a proximate driver of economic growth. As noted in Subsection 3.2.2, investment in the model is influenced by capacity utilization, profitability, borrowing costs and net exports. As demands for different goods and services grow at different rates, the response on the supply side manifests as structural change (Chenery et al., 1986; Pasinetti, 1981).

Domestic demand is modified by import propensities. The import propensity is updated through successive solutions of the LGP. For example, if a domestic sector begins to expand relative to other sectors, then the import propensity may decline. The import propensity also depends on domestic versus world prices through an Armington-like relationship (Armington, 1969).

3.2.5 Employment and labour productivity

A strong empirical finding is that rates of labour-productivity growth tend to rise as a sector or the whole economy expands. This is known as the Kaldor-Verdoorn law (Kaldor, 1966; McCombie & Spreafico, 2016; Ocampo et al., 2009; Verdoorn, 1949, 2002). It is a well-established regularity in economic data. Particularly in manufacturing, and to some degree in other sectors, labour-productivity growth depends on the pace of sectoral growth. The theory is that faster growth drives investment in labour-saving technology; accelerates the spread of labour-saving, fixed capital; and stimulates efficiency improvements through learning by doing. It is particularly salient in mining, manufacturing and other capital-intensive sectors subject to increasing returns to scale, but it is also seen at the level of the whole economy.

The Kaldor-Verdoorn law is an endogenous-growth mechanism. It is frequently incorporated within post-Keynesian and structuralist models, and it is offered by default in the AMES model. The default version applies the Kaldor-Verdoorn law to the whole economy in the aggregate. Alternatively, constant Kaldor-Verdoorn parameters can be assigned to each sector.

Once labour productivity is determined, employment is calculated either at the level of the whole economy or by sector by dividing sectoral output or GDP by productivity.

3.3 The model interface

The AMES model and the LEAP-AMES interface are implemented in the open-source Julia programming language, using LEAP's application programming interface (API) to carry out the iterative process in Figure 1. Otherwise, the interface to the AMES model is via text files and parameters passed in the call to the AMES Julia function. This makes it possible to run AMES from within LEAP using a simple script[17] and to link AMES to other programmes.

Data files are provided in a comma-separated values (CSV) format. Time series, product and sector data are provided in a simple, tabular format with pre-defined column headings.[18] The set of supply-use tables is also in a CSV format, but the structure is more flexible.[19] References to the supply-use file appear in a configuration file using conventional spreadsheet notation (e.g., `supply_table: J3:W16`).

The configuration file, a text file in YAML format, contains a great deal of information, including scalar parameter values, rules for linking to LEAP, and names of input files.[20] Calibrating a model mostly involves modifying values within the configuration file. As output files are also text files (mostly in CSV format), it is possible to calibrate an AMES model automatically using the third-party and freely available Parameter Estimation (PEST) software (Doherty, 2015). PEST is extremely flexible, but a PEST run is hard to set up and modify without assistance. The AMES package makes the process easier through a separate Julia script that builds PEST input files and runs PEST on an AMES model.[21]

4. Outputs from the sample "Freedonia" model

For training and testing purposes, LEAP comes with a sample model for a fictitious country, "Freedonia."[22] The AMES package likewise comes with a set of input files for Freedonia. In all, three separate but related AMES models are provided, with the following configuration files:

1. AMES_params.yml;
2. AMES_params_all_options.yml;
3. AMES_minimal_params.yml.

Configuration files 1 and 2 include instructions for linking to LEAP. File 3 is for AMES in stand-alone mode. Configuration file 1 corresponds to the core model documented in previous sections, while configuration file 2 makes use of some additional features listed in the next section. Configuration file 3 is a minimal model with a simplified configuration file.

The online documentation includes instructions for installing AMES and for running the first configuration file, with and without LEAP.[23] Running with LEAP, AMES calculates the metric R defined in Eq. and finds R = 2.52%. This suggests that neglecting demand from the energy sector for non-energy goods and services should be reasonable.

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[17] See https://sei-international.github.io/AMES.jl/v2.3.1/running-ames/#running-ames-from-LEAP.

[18] See https://sei-international.github.io/AMES.jl/v2.3.1/params/.

[19] See https://sei-international.github.io/AMES.jl/v2.3.1/sut/.

[20] See https://sei-international.github.io/AMES.jl/v2.3.1/config/.

[21] See https://sei-international.github.io/AMES.jl/v2.3.1/pest-calib/.

[22] The economic Freedonia dataset was constructed by starting from actual data for a lower-middle-income country and then anonymizing the data through smoothing and adjustment to better match the structure of the Freedonia LEAP dataset. The Freedonia LEAP example is meant to represent the energy system of a developing country. The results shown in this section illustrate key features of AMES and are characteristic of results found when applying the model in practice.

[23] For installation, see https://sei-international.github.io/AMES.jl/v2.3.1/installation/; for running without LEAP, see https://sei-international.github.io/AMES.jl/v2.3.1/quickstart/; for running with LEAP, see https://sei-international.github.io/AMES.jl/v2.3.1/leap-exercise/.

This section shares a small sample of results[24] from running configuration file 1. The runs in this section were carried out without linking to LEAP; results from the linked LEAP-AMES model can be found in the online documentation. However, one feature of a linked AMES analysis should be mentioned: because AMES is a demand-led model, energy investment can have a persistent stimulating effect that results in a higher level of GDP and employment. This behaviour can be seen in the LEAP exercise for AMES. It is an example of hysteresis, a common feature of demand-led models (Lavoie, 2018) and is seen in practice (Ball, 2014), in which future long-run outcomes depend crucially on past events. In contrast, CGE and other models that assume full utilization of productive capacity do not exhibit hysteresis; GDP may deviate slightly from its long-run potential trend, but always returns to it.

Figure 2 plots Freedonia's GDP growth rate for non-energy sectors. The figure also shows the world GDP growth rate (an exogenous parameter), the central bank rate and the inflation rate. The drop in GDP after 2020 is due to the impact of the Covid-19 pandemic on world GDP and therefore on trade for Freedonia; the direct impact of the pandemic on the Freedonia economy was not simulated. Due to changes in demand and structural change, Freedonia's GDP growth rate gradually slows. Meanwhile, the central bank rate stabilizes as the bank's Taylor rule brings the inflation rate to its target.

Figure 2. GDP growth rate (world and Freedonia), the central bank rate and the inflation rate for the Freedonia sample model

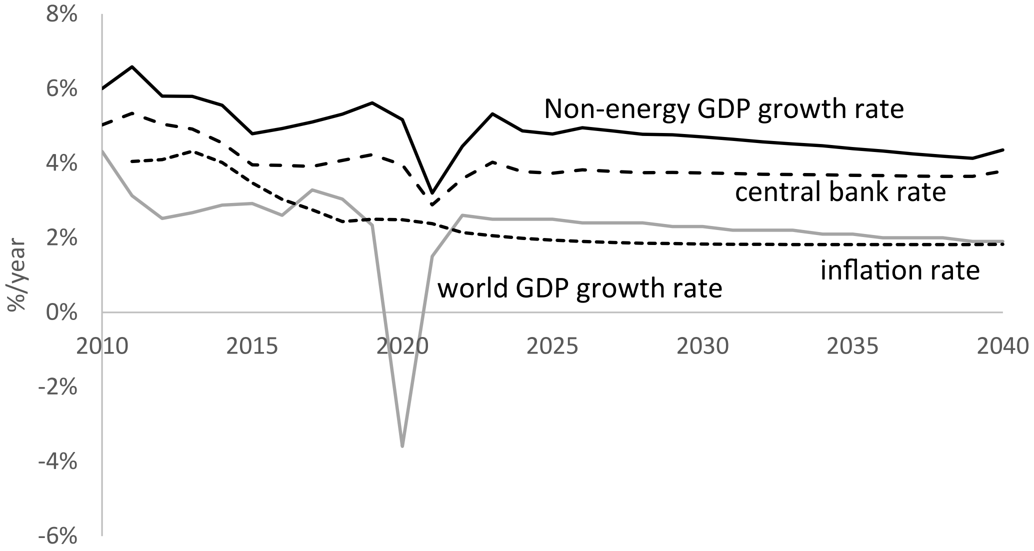

Figure 3 shows structural change in the Freedonia AMES model as changing shares of (non-energy) value added. The results reveal an expansion in services and a moderate decline in agriculture, mining, and iron and steel production. Figure 4 provides a further measure of structural change. AMES calculates a "domestic insertion" parameter that is the ratio of domestic to total demand per unit output from each sector, including both direct and indirect demand. This captures a key concept in development theory that development represents not only GDP growth and not only inclusion in global value chains, but also the extent to which domestic sectors are integrated into the domestic economy (e.g., Demas, 2009 in the context of small island states). As seen by this measure, Freedonia's domestic insertion does not decline for any sector, and for some sectors it rises modestly between 2010 and 2040.

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[24] See https://sei-international.github.io/AMES.jl/v2.3.1/model-outputs/.

Figure 3. Value-added shares by sector in the Freedonia sample model. Numbers in parentheses in the legend are the percentage point change in the value-added share from 2010 to 2040.

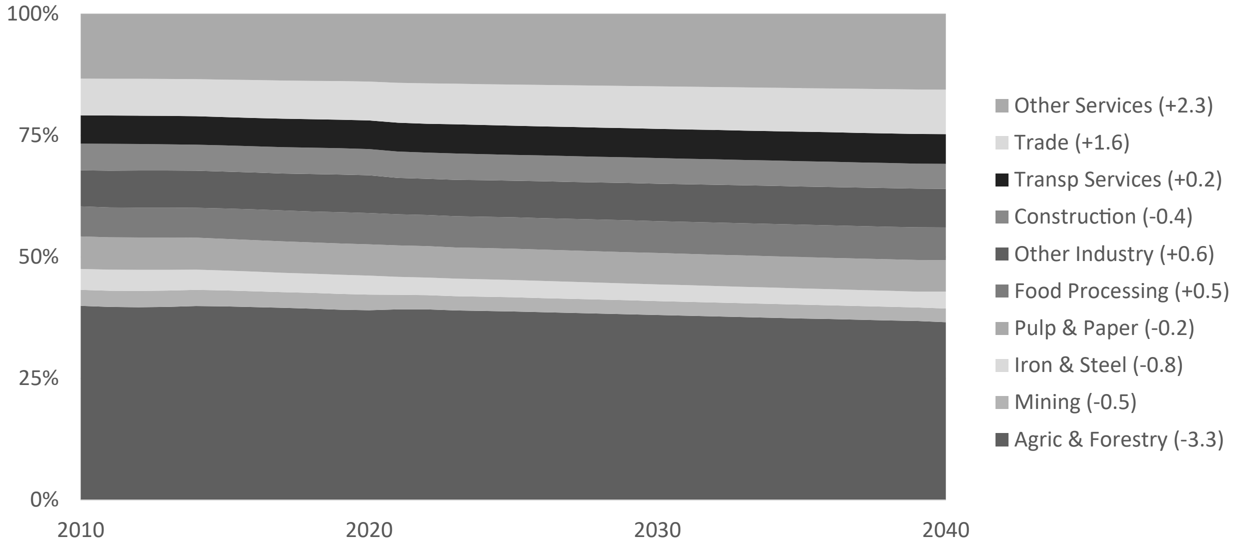
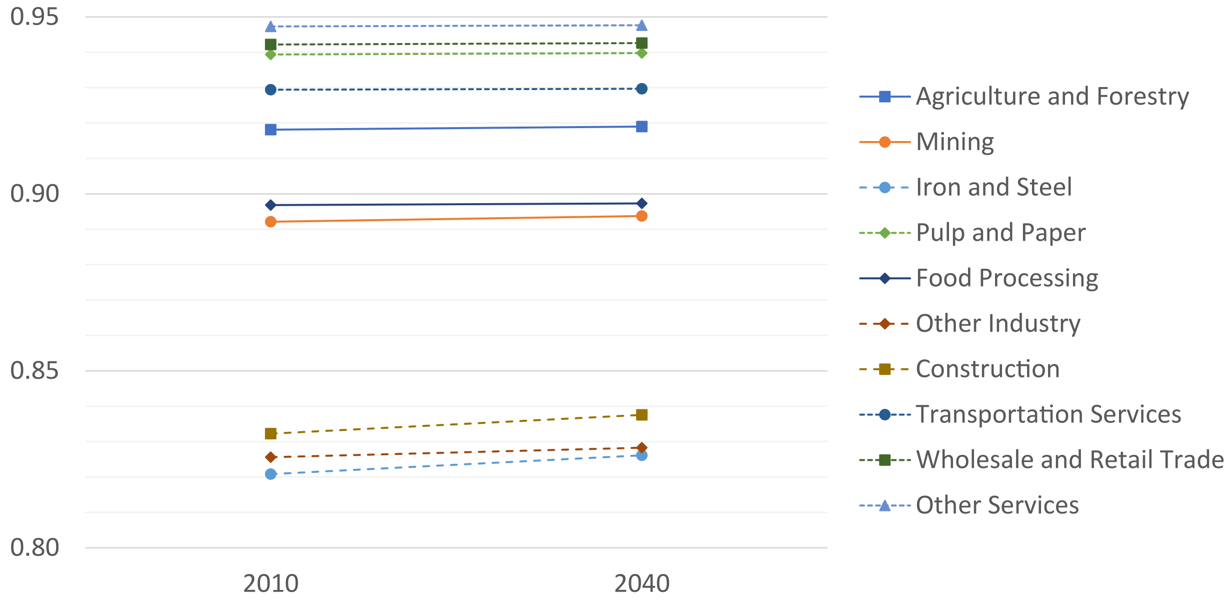


Figure 4. AMES's "domestic insertion" metric for the Freedonia sample model



5. Additional features

AMES and the LEAP-AMES interface offer some additional features beyond the core model. This section discusses two such features: exogenous potential output and endogenous intermediate demand coefficients. Details can be found in the online documentation.

5.1 Exogenous potential output

AMES calculates potential output by sector. However, sometimes potential output must be specified exogenously. Three cases are of particular interest: when a national or sectoral strategy specifies target growth for specific sectors; when an external model simulates output in some sectors; and when an energy sector is sufficiently important to the economy that AMES's simplifying assumption does not hold. In such cases, AMES converts exogenously specified, potential sectoral output to an index, calculates the implied investment rate, and adjusts the trade calculation on the assumption that domestic production is meant to improve the trade balance.

The most straightforward case is when a national or sectoral strategy specifies output for a sector. The only complication is that the strategy may not provide targets across the entire energy-planning horizon. If it does not, then some extrapolation will be required; AMES does not allow for mixed exogenous and endogenous specifications of potential output.

A more complex case is when a separate model generates a time series that can be applied exogenously as potential output for a sector in AMES. Crop production from an agricultural model offers one example. If the external model is entirely independent, then it can be run once, and the results can be applied as a time series for AMES. However, if the external model depends on energy production (e.g., hydropower or pumping) or economic variables, a separate script can link all the models together. Interactions with LEAP can be carried out through its API, while interactions with AMES can be implemented by exchanging text files.

The final case is when an energy sector has high backward linkages. For example, an oil producer might have a reasonably diversified economy, yet also rely on the oil sector as a source of demand for goods and services throughout the economy. In that case, the assumption that the energy sector has negligible demands for non-energy products fails to hold, which will be reflected in a large value for the metric R in Equation (7). For energy extraction or transformation sectors with reasonably homogeneous output, AMES will accept LEAP's calculated capacity for those sectors as exogenous potential output.

5.2 Endogenizing intermediate demand coefficients

In the core AMES model, intermediate demand coefficients are kept at their base-year values as calculated from the supply-use tables. They are determined by dividing "use" of products by sectors by total sector output. However, over the long time horizon of a low-emission development strategy or a typical LEAP scenario, technology is bound to change.

The core AMES model builds in changes in labour productivity, while keeping intermediate demand coefficients fixed. Beyond that core behavior, AMES optionally offers endogenous calculation of intermediate demand coefficients.[25] The mechanism is cost share-induced technological change as in Kemp-Benedict (2022).

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[25] See https://sei-international.github.io/AMES.jl/v2.3.1/dynamics/#dynamics-intermed-dmd-coeff and https://sei-international.github.io/AMES.jl/v2.3.1/params/#params-sectors.

6. Conclusion

This paper introduces AMES, a macroeconomic extension for the Low Emission Analysis Platform (LEAP). The AMES model, which can be run and calibrated separately from an associated LEAP model, is designed to provide consistent economic drivers for a LEAP analysis. The particular focus in this paper has been on using LEAP and the associated optimization package NEMO together with AMES for energy, economic and environmental assessment in low- and middle-income countries, specifically in the context of low-emission development strategies.

The literature on energy and energy-economic models for low- and middle-income countries reveals gaps in the available modelling suite including structural barriers to transformation (Gillingham et al., 2009; Worrell et al., 2004) and the need to represent structural change (Urban et al., 2007). Filling those gaps is consistent with the structuralist economic tradition (Chenery, 1975; Ocampo et al., 2009), and the AMES model presented in this paper is a multi-sector model built along structuralist lines. It is an example of the broad category of macroeconometric models (Nikas et al., 2019), in contrast to CGE, optimal-growth or partial-equilibrium models.

The bottom-up nature of LEAP and NEMO, combined with the top-down nature of AMES, makes the integrated LEAP-NEMO-AMES system a hybrid energy-economy model (Hourcade et al., 2006). It is a flexible modelling system with useful core functionality and a number of extensions; it is thoroughly documented online. AMES is being used in practical policy analysis while remaining under active development. Moreover, while LEAP requires a licence, both NEMO and AMES are open-source models written in the open-source programming language Julia; LEAP is available for free to accredited students in any country, and to academic organizations, NGOs and not-for-profit government agencies in low- and lower-middle-income economies. It is available at reduced rates to organizations in upper-middle-income economies.

In summary, AMES, together with LEAP and NEMO, offers an affordable, full-featured, hybrid energy-economic modelling system that is particularly suited to low-emission development strategies in low- and middle-income countries.

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