Since the start of the Industrial Revolution, improvements in energy conversion and use have transformed the world. Unfortunately, expanded energy use, and the economic growth it enabled after the Industrial Revolution, have not benefited everyone equally. Similarly, the contribution of different countries to greenhouse gas emissions, and therefore, climate change, has differed among regions worldwide. Unsurprisingly, countries with lower energy consumption have had lower annual and cumulative emissions of greenhouse gases since the 19th century than those with high energy consumption. Unfortunately, developing countries in Sub-Saharan Africa, Asia, and Latin America, which have contributed the least to cumulative greenhouse gas emissions, are also the most vulnerable to its impacts and have lower adaptive capacity than wealthier countries (IPCC 2022). These least developed and developing countries need to increase their energy consumption to support economic growth. However, such growth in energy demand could potentially result in a substantial increase in greenhouse gas emissions. Herein lies one of the biggest challenges of the 21st century: providing energy that enables economic growth in the least developed and developing regions while meeting climate stabilization goals.

Given the long life of energy infrastructure assets, the decisions made in the least developed and developing countries will determine the success or failure of global climate mitigation efforts. Some of these decisions may result in path dependencies that lead to carbon lock-in. For example, recent research suggests that operating the existing fossil energy infrastructure in developing countries (excluding China and India) would result in 130 gigatonnes of CO$_2$ by 2060 (Tong et al 2019). Similarly, the completion of fossil fuel-based projects proposed in developing countries (excluding China and India) would add 75 gigatonnes of cumulative CO$_2$ by 2070 (Tong et al 2019).

Avoiding emissions from existing energy assets would require premature retirement, resulting in stranded assets. Across all developing countries (excluding India and China), the value of existing energy assets that would continue contributing to global CO$_2$ emissions is more than U.S.$4 trillion. In addition, the value of proposed power plants in these developing countries totals U.S.$280 billion (Tong et al 2019). Premature retirement of these assets would increase the costs of meeting the energy needs of least developed and developing countries. Therefore, we must understand feasible energy development pathways considering existing investments in the least developed and developing countries and their financial and environmental implications.

Macro energy system models are typically linear programs that minimize the total system cost of energy supply over a user-specified time horizon, subject to both system-level and user-defined constraints. These models represent the energy system as a process-based network in which technologies are linked together by flows of energy commodities. Each process is defined by an exogenously specified set of techno-economic parameters such as investment costs, operations, and maintenance costs, conversion efficiencies, emission rates, and availability factors. Figure 1 shows a common visualization of a directed network graph for the energy system models. A database of energy inputs (sources, shown on the right of figure 1) and the representation of energy transformation technologies (shown as rectangles in figure 1) serve as the backbone of the model. Modelers exogenously specify the end-use demands described on the right of the figure.

Existing macro energy modeling tools include Temoa, TIMES/MARKAL, SWITCH, and OSeMOSYS (Groissböck 2019). The mathematical formulation of these models is generalizable to any region of interest. However, their application in the context of least developed and developing countries requires the creation of the appropriate underlying database that parametrizes the required modeling inputs. Recently, there has been some work to establish these databases and apply these models to the context of the least developed and developing
countries. However, these efforts still face limitations. Dioha (2017), for example, suggests that none of the now available energy system models include a complete representation of the technological options, demand projections, or governance constraints that capture the conditions in the least developed and developing countries. Furthermore, most previous work on energy modeling in the least developed and developing countries has focused on the power sector (for example, Allington et al. 2022; Pappis 2022). As a result, prior work has generally ignored energy demand for transportation, industry, and commerce, which can be more challenging to characterize. Similarly, research has focused primarily on deploying conventional renewable energy resources, overlooking the potential for other low-carbon energy resources. Finally, prior work has evaluated a limited number of emissions and policy scenarios and has not explicitly accounted for uncertainty.

Given the limitations of prior work, there is a growing need for energy modeling efforts focused on the least-developing and developing countries. Such work would create the proper energy system databases and adapt the existing modeling tools to the context of these least developed and developing regions. It is essential, however, that best practices inform these efforts. DeCarolis et al. (2020) suggests that distributed, collaborative, and open-access modeling efforts would enable transparency, accessibility, and replicability. Suffice it to say, modeling efforts focused on the least developed and developing regions must include researchers from these regions. Fortunately, the tools to enable such collaborative efforts are increasingly available. They include 'open-source energy models, well-established software development tools, a wide range of collaborative communication tools, and an increasing number of publicly available datasets on which to build' (DeCarolis et al. 2020).

As noted earlier, a crucial challenge of the 21st century will be to provide energy that enables economic growth in the least developed and developing regions of the world while meeting global climate stabilization goals. Macro energy system modeling efforts focused on these least developed and developing countries provide 'a systematic way to examine future decarbonization pathways, evaluate technology choices, test the effects and consequences of proposed policies, and explore decisions under future uncertainty' (DeCarolis et al. 2020). These tools can yield critical insights that inform climate and energy policy in the least developed and developing regions. They can inform research and development priorities, financing needs, and international negotiations. Now is the time for governments, non-profits, and research institutions to support the macro energy system modeling community in the least developed and developing countries. Similarly, journals like Environmental Research Letter can support the dissemination of the results of these research efforts. These academic journals must ensure access to fair and thorough peer review of papers focused on the least developed and developing countries. As they say, there is no planet b, and ensuring a low-carbon energy transition in the least developed and developing countries must be a priority for climate mitigation research.

![Figure 1. A common visualization of the directed network graph for the energy system within energy system models. Adapted from Temoa (2022). GPLv2.](image-url)
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