Loose Coupling of Engineering and Interindustry Models: Benefits and Pitfalls

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Abstract *When building a new model, the model builder comes to the task with certain specific goals, which help to determine the focus of the model. So the modeler must specialize, leaving out or simplifying relationships of secondary importance, and focusing on behavioral, accounting and technological relationships of primary importance. The choices involved in building a model are broad, including the databases to be used, the level of spatial, sectoral and temporal detail, and the family of techniques applied which general place the model in a category of other pre-existing models.*

Since no model is completely comprehensive, it is helpful in some situations to link models of different types. This has resulted in a large literature including hybrid energy-economy models, bottom-up and top-down models, as well as linkages between national level and regional models, macroeconomic and input-output models.

This paper is a short review of the general issue of model linking, touching on some common goals of linking, as well as discussing drawbacks and difficulties. A very partial review of literature that illustrates these goals and drawbacks is discussed. Finally, we conclude by discussing two studies that have been performed using the Inforum LIFT model loosely coupled with engineering models. Two prominent examples are the US MARKAL model, and the EnergyPATHWAYS model.

Background

For many types of modeling analyses, it is helpful to link models of different types. When working with an input-output model, researchers may often link to a macroeconomic model. Other useful linkages include models of satellite accounts (R&D, travel and tourism, or health care, for example). Research on energy supply and demand, GHG and other emissions, new technologies and materials flows often involves detailed information at a finer level of detail than that generally available in an input-output based model. In addition, measurement and modeling in physical units is necessary. In this case, it may be fruitful to link an energy systems model (ESM) with the input-output model. An ESM maintains a detailed energy system representation that captures the flow of energy and technology adoption and the satisfaction of end use demands. It has the ability to model detailed information about costs and characteristics of competing technologies that may be used to satisfy end use demands.

An economic model, on the other hand, whether it be econometric or CGE, can provide a consistent and fairly detailed picture of the overall economy, and relates to end use demands by consumers, businesses and government. Such a model can also incorporate forecasts of industry exports and imports, both for energy and non-energy sectors. If the model contains a macroeconomic block which includes national accounting (SNA) by institutional sector, it enables the modeling of policies that have implications for the government budget, including the modeling of revenue recycling mechanisms. If the model is input-output based, it can also capture the price effects of policies to reduce GHG and other emissions, including their indirect effects. The model also provides essential economic projections which are exogenous to the ESM, such as household disposable income, sectoral prices, and interest rates.

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1 Introduction

1.1 Motivation

The dream of combining the best features of engineering process and technology models with macroeconomic, CGE and Input-Output models was born in the early 1970s, made possible by a rapid rise in computer power. The engineering models, when applied to energy problems, became known as Energy Systems Models (ESM). These models can represent the end uses of energy, the technologies and fuels necessary to satisfy those end uses, and the investment and materials cost necessary to develop and use these technologies. Starting with early work at the US national laboratories Brookhaven and Oak Ridge on the BESOM (Brookhaven Energy Systems Optimization Model), work continued at the national labs to contribute to the initial development of MARKAL (Market Allocation), which later became the TIMES model.

These models provided wonderful insights into just how variable inputs would be combined with fixed capital in the form of specific types of machinery or processes in order to generate electric power, provide heat and air-conditioning to buildings and homes, or provide motive power for automobiles and other transportation equipment. Literally hundreds of technological relationships are represented in a model such as BESOM or TIMES/MARKAL, which provide information on relative costs, efficiencies, and fuel requirements. This type of model is also well-suited to calculating emissions resulting from the use of various energy technologies that use fossil fuels, or in industrial uses which generate carbon and other pollutants.

However, an ESM is not a comprehensive economic model, and requires outside information on the overall level of economic activity, and ideally, the production demands for detailed industries, whose requirements for energy and generation of pollution may differ significantly from each other. Furthermore, although the ESM can calculate the relative cost of using alternative technologies or processes, it still requires information about prices of inputs, capital costs, and prices for various types of fuels. Furthermore, an economic model can potentially model the interaction between changes in purchasing and consumption patterns due to technological changes, and the subsequent changes in demand for fuels and types of technology. The economic model can delve into broader questions, such as the recycling of revenue from a carbon or other energy tax, or the impacts of net exports of a technology adoption which reduces the cost of extracting a fossil fuel such as natural gas.

The solution has been to link ESMs and related models with either a simple macro model, a CGE model, or an input-output model. While the achievements of this type of linking have been significant, there are some drawbacks, and problems encountered in the linking. The goal of this paper is to first do a cursory review of some experiences in linking ESMs with economic models, and summarize some of the lessons learned. Next, we will review some studies using the Inforum LIFT model as the economic model, with either MARKAL or the EnergyPATHWAYS model as the energy systems model. While the LIFT model is unique among the economic models that have been used for this purpose, our experience may shed some light that could be helpful in future exercises with other models.

1.2 Brief Review

Energy balance and energy accounting frameworks served as the approach to a simple representation of the energy system (Hoffman and Wood, 1976). This approach was extended in the early 1970s to the development of the Reference Energy System (RES), as exemplified by the BESOM, produced at Brookhaven lab (Cherniavsky, 1974 and Beller, 1975). A very influential early paper (Hoffman and Jorgenson, 1977) tied BESOM to Jorgenson's industrial energy/input-output model, developed with Hudson and other researchers.

The Reference Energy System traces the flow of energy products and services from resource extraction, to refining and conversion, transport, transmission and distribution, to utilizing equipment, to end uses. This framework allows for substitution at any stage. For example, aluminum electrolysis is most often done using electricity, which may be generated using either fossil fuels, wind, solar or nuclear. Personal transportation end use may be satisfied by public rail or bus, or by automobile, which may be either powered by fossil fuel or electricity. BESOM allowed for the specification of engineering relationships which could derive required inputs, as well as estimate the shadow price of the energy flow. Jorgenson's input-output energy model was linked to BESOM, to provide macroeconomic and industry demand assumptions, as well as model personal consumption, industrial and government end uses. One strength of the RES was that future, yet to be developed technologies could be explored, if some information was available on their costs and energy requirements. Learning curves could be implemented to model the increase of knowledge and efficiency over time in various technologies.

Hoffman and Jorgenson utilized a "soft-linking" approach, where the two models were allowed to separately coexist, and feed assumptions to each other iteratively. They recognized early that there would be areas where both models yielded results, and that these results might differ. Subjective decisions would then need to be made on which model would control the other in this area.

Continuing work on BESOM eventually led to the development of the MARKAL model which included multi-period optimization as well we a detailed representation of technologies and a RES. Development of MARKAL in the U.S. continued with U.S. government sponsorship from the Department of Energy, and several university research centers also got involved. Manne and Richels (1992) linked MARKAL to a macroeconomic optimization model. (MARKAL has since been adopted for use in many different countries, linked to macro, input-output or CGE models of those countries. A large literature has developed, which will only be touched on in this paper (see the reviews by Bhattacharyya and Timilsina, 2010, and Fattahi, Sijm and Faaij, 2020).

Similar work was going on in parallel in Europe. IIASA's Environmentally Compatible Energy Strategies (ECS) project developed an integrated set of tools, and a central part of this framework was called MESSAGE-MACRO (Messner and Schrattenholzer, 2000). This set of models describes the interaction between macroeconomic production, energy demand and supply, and pollutant emissions. MESSAGE-MACRO in turn was based on the 11R model, which built on earlier work by Manne and Richels mentioned above.

1.3 Bottom-up and Top-down

In many of the characterizations of this model linking, the macro/IO/CGE model is described as "Top-down" and the engineering or energy system model is "Bottom-up". The Top-down model may provide aggregate controls to the ESM, as well as provide important variables that are exogenous to it. The Bottom-up model explores detailed relationships not known by the Top-down model, to provide information on technology choice, fuel requirements, investment requirements, and sometimes, information on intermediate input requirements. This concept has some parallel and overlap with developments in CGE modeling, particularly by Bohringer and Rutherford (1977).

Some of the “Top-down” models may indeed have elements of “Bottom-up”, and overlap with the ESMs in many areas. For example, the Inforum LIFT model was called bottom-up before this term became fashionable in energy/environment analysis. In the projects described below, where the LIFT model was linked with MARKAL or the EnergyPATHWAYS model, LIFT has incorporated extensive energy detail in the electric power generating sector, the transportation sector, in residential, commercial and manufacturing buildings, and in household energy consumption.

2. Models and Linking Methods

2.1 Economic Models

The three main types of economic models that have been linked with ESMs or engineering models are macroeconomic models, CGE models (which may include IO or industry detail), and econometric input-output models.

Macroeconomic Models

Macroeconomic models are designed to describe the operation of the problems of economy of a country or a region. These models are usually designed to examine the comparative statics and dynamics of aggregate quantities such as the total amount of goods and services produced, total income earned, the level of employment of productive resources, and the level of prices.

Macroeconomic models may be logical, mathematical, and/or computational; the different types of macroeconomic models serve different purposes and have different advantages and disadvantages. Macroeconomic models may be used to clarify and illustrate basic theoretical principles; they may be used to test, compare, and quantify different macroeconomic theories; they may be used to produce "what if" scenarios (usually to predict the effects of changes in monetary, fiscal, or other macroeconomic policies); and they may be used to generate economic forecasts. Thus, macroeconomic models are widely used in academia in teaching and research, and are also widely used by international organizations, national governments and larger corporations, as well as by economic consultants and think tanks.

A typical macroeconomic model consists of econometric equations and identities, primarily for scalar (not matrix or vector) variables. The number of equations and identities may vary from as little as 20 to 50 to as many as 2000. Well-known commercial macroeconomic models include: 1) S&P Global, formerly known as the Macroeconomic Advisors model; 2) FRB/US, produced by the Federal Reserve Board; 3) the Oxford Economics model, one of a family of country models; and the FAIRMODEL, a model that can be explored and run online. Historical macroeconomic models include the Klein model, the MIT-FRB-Penn model, the Chase Econometrics model, the DRI Quarterly and Annual Long-term Macro Models, and the WEFA model. These are no longer in existence, but have had a big impact on thinking about this type of model.

The linking of macroeconomic models to ESMs must by its very nature be somewhat imprecise, as a macroeconomic model generally does not have much industry or energy detail. However, ESM-Macro linkages have a long history, and continue to be popular.

CGE Models

CGE modeling is a huge field, with dozens of major representative models. Seminal work was done by Shoven and Whalley, but the basic ideas they developed have been applied to many other problems and types of models. Many of the CGE models are macroeconomic, but many others have industry detail. A popular CGE model for international input-output is GTAP, started at Purdue

University. Peter Dixon developed the Monash model and helped to develop the software that was used to build this model. He and his team have also built a large-scale interindustry CGE model of the U.S., called *Usage*. CGE models have the advantage of mathematical elegance in presentation and generally light data requirements. They have the disadvantage of being based on equilibrium concepts, which are difficult to establish empirically, and relying on specified parameters for key behavioral relationships, often obtained from literature written by another researcher, that may not be applicable to the problem at hand. They generally rely on the concept of a representative agent or firm, which is hard to reconcile with the behavior of observed data. They tend not to be estimated econometrically, but rather to be calibrated to a data set for a fixed period.

Many of the Energy Systems Models have elements borrowed from CGE modeling, such as the concept of market equilibrium, maximizing expected present value, and perfect foresight. Industry or input-output based CGE models have been a popular tool for linking with ESMs.

Input-Output Econometric Models

Under this class can be found the family of Inforum models, as well as those developed at Cambridge Econometrics by Terry Barker and his colleagues. The REMI model of the U.S. has overlap with this type of model, including econometric estimation, and input-output relationships. This type of model is a structural model, and includes economic concepts in the development of the estimated equations. For example, the personal consumption system estimates a family of personal consumption equations for goods and services as part of a unified decision, based on relative prices, per capita income, and other factors. However, there is no underlying optimization problem of the consumer underlying the modeling of personal consumption. The forms of investment equations often include features derived from factor demand analysis, using a translog or Diewert cost function. However, the demand equations for investment and other factors are not derived as an optimization problem.

Econometric input-output models are dynamic, running year by year, and cumulate capital stock and other variables over time. Adjustment to changes is generally smoother than in an optimization model, often based on a distributed lag relationship, which may be interpreted as a form of adaptive expectations.

Models such as the LIFT model of the U.S. include a wealth of sectoral detail, which provides many contact points with an Energy Systems Model.

2.2 Energy Systems Models

One of the first Energy Systems Models was described above, the Brookhaven Energy Systems Optimization Model (Cherniavsky, 1974; Beller, 1975). This model was apparently under continuous development from the early 1970s up through the early 1980s, and was featured in the seminal paper by Hoffman and Jorgenson (1977) and many others. Ideas that evolved in the development of this model were incorporated into the MARKAL model (Loulou, Goldstein and Noble, 2004), in which the number of processes and types of technology was expanded significantly. Since the development of MARKAL was distributed in various locations, there were many versions available at any one time. MARKAL is now called the TIMES model, or sometimes TIMES/MARKAL, and is hosted by the International Energy Agency's Energy Technology Systems Analysis Programme. The number of users of the TIMES/MARKAL family of models has multiplied to 77 institutions in 37 countries. Another early ESM was the MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) model, developed initially at IIASA in Austria in the 1980s, but in use more recently by the International Atomic Energy Agency (IAEA) among others.

(Model for Energy Supply Strategy Alternatives and their General Environmental Impact) has been developed by the International Institute for Applied Systems Analysis (IIASA) in Austria since the 1980s.

The period since 2000 has seen a rapid growth in the development of ESMs. Among these are PRIMES, METIS, POLES, OPERA, ETM, LEAP, IKARUS and PATHWAYS. Some of these models are commercial or mixed commercial/academic. Many others are open source. Table A-1 in the Appendix is a partial list of these models, identifying the maintainer and website.

2.3 Soft-linking and Hard-linking

Wene (1996) explored the relative strengths and weaknesses of soft-linking and hard-linking ESMs and economic models. Wene linked a macroeconomic model (ETA-MACRO) and a systems engineering model (MESSAGE iii), using soft-linking. Noting that many researchers had found smaller response patterns in macro models as compared to energy systems models, Wene notes that this discrepancy is generally referred to as "The Gap". In the linked modeling system, the macro model captures feedbacks between the energy system and the rest of the economy. The macro model provides dynamic drivers for demands for end uses that are consistent with the overall consumption, investment, government and net trade. Soft-linking procedures concentrate on the areas of the macro model and the engineering model where there is overlap. The engineering model can calculate specific demands for investment in new technologies, which can be supplied to the macro model. The engineering model also yields demands for energy and other inputs. In hard-linking, on the other hand, all transfer of information between the two models is formalized, and handled by the computer program. Soft-linking can identify areas where the two models diverge or disagree, and this can be very instructive. In hard-linking, one model is chosen to control the other model, or the models can be conjoined into one model.

Holz, et al. (2016) actually divide model linking into three categories: 1) soft-linking in which the processing and transfer of information is controlled by the user. 2) hard-linking in which all information processing and transfer is handled by a computer program. 3) integrated modeling in which a unified mathematical approach is used (e.g., applying mixed complementarity problems (Böhringer and Rutherford, 2009)). Böhringer and Rutherford (2008) define three categories: 1) coupling of existing large-scale models (i.e., soft-linking), 2) having one main model complemented with a reduced form of the other, and 3) combining the formulation of the models as mixed complementarity problems.

Fattahi, et al. (2023) explore softlinking a national CGE model (ThreeME) with a detailed energy systems model (IESA-Opt). They decide on the softlinking approach because it requires minimal changes to the existing models, and provides unique perspectives from comparing the model results. However, they bring up several issues, such as data consistency, physical versus monetary units, time frequency differences, and the decision requirements due to model overlap.

3. Studies Using the LIFT Model

3.1 Coupling the MARKAL and LIFT Models

Inforum, the Mitre Corporation and the U.S. Environmental Protection Agency partnered in analyses done for the Energy Modeling Forum (EMF) 25[1]. A central issue in this Forum was the question of the amount by which new policies focused on improving end-use energy efficiency will curtail GHG emissions if they are implemented, compared with a strategic carbon-mitigation strategy that includes an effective price on carbon dioxide emissions. The EMF Working Group focused on cost-effective reductions in energy demand based upon simulations provided by 10 energy-economy models for the U.S. The exercise was based on developing 8 scenarios, which were then implemented and compared between the various models.

The MARKAL model, with its detailed representation of energy technologies and end uses, determines choices between alternative types of equipment, energy sources and fuels. The LIFT model provides the overall economic environment, including a detailed personal consumer demand system for 92 goods and services, and final demand, production, employment, investment and value added for 121 commodities and 71 industries. Drivers from the LIFT model can be used to determine demand for end-uses in the MARKAL Energy Reference System. MARKAL, in turn, suggests changes in investments, intermediate input requirements, and supply prices for energy types and end-uses. For example, energy efficiency improvements modeled in MARKAL are reflected in lower energy input-output coefficients in LIFT.

The paper focuses primarily on two of the EMF scenarios: 1) the application of a carbon dioxide emissions tax to the energy system; and 2) a scenario where consumers select energy equipment based solely on costs using a 7 percent discount rate. This discount rate was applied to all technologies in assessing initial investment costs relative to energy cost savings over the LIFT of the purchased equipment. The paper found the most significant response was in the commercial and residential building sectors. Results were moderate in the industrial sector and relatively minor in the transportation sector, as more aggressive policies for transportation, such as renewable fuel standards or subsidies for highly efficient vehicles were not considered.

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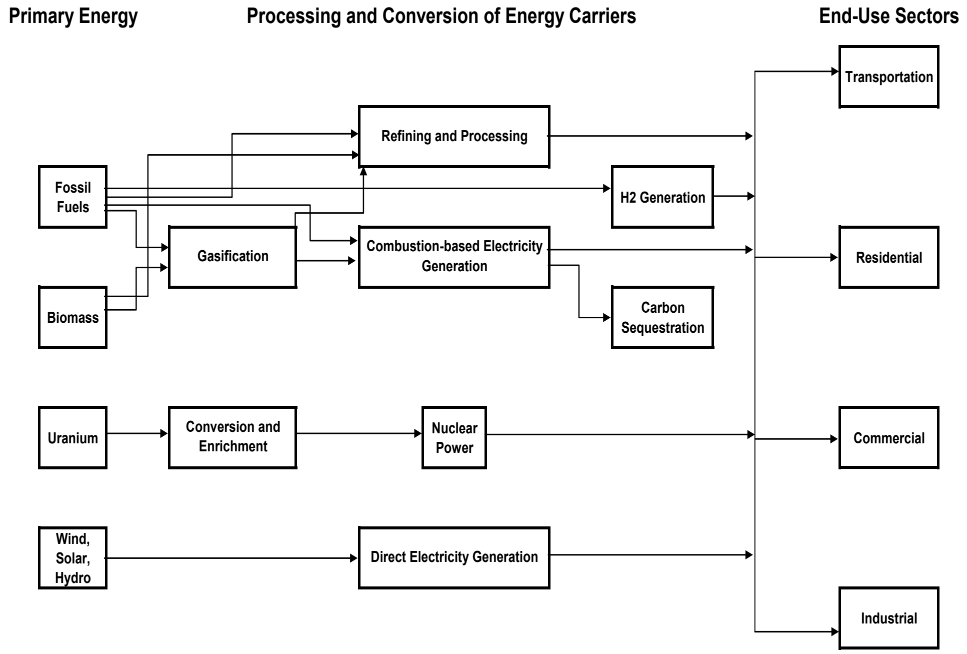
[1] EMF 25 *Strategies for Mitigating Climate Change Through Energy Efficiency: A Multi-Model Perspective*, papers published in a Special Issue of the *Energy Journal*, October, 2011. See in particular the introduction by Huntington and Smith. The MARKAL/Lift exercises are described in Steckley, et al. (2011).

The MARKAL Model

The basis of the MARKAL model framework is the Reference Energy System (RES), shown in Figure 1.

Figure 1. Reference Energy System



Coverage of the energy system ranges from the import or extraction of primary energy resources, to the conversion of these resources into fuels, and through the use of these fuels by specific technologies to meet end-use energy demands. End-use demands include items such as residential lighting, commercial air conditioning, and automobile vehicle miles traveled. Data used to represent these items include fixed and variable costs, technology availability and efficiency, and pollutant emissions[2].

The MARKAL database used for this study contains detailed representations of the U.S. energy system at the national level, over a modeling time horizon that extends from 2000 through 2050. The database covers the power generation, residential, commercial, transportation, and industrial sectors. Spread across the four end-use sectors, there are 87 energy service demands that can be met by numerous (~1700) end-use technology options of varying efficiency and cost. For example, the commercial and residential sectors have specific technological detail for the following energy service demands: space heating, space cooling, water heating, lighting, ventilation, refrigeration, cooking, and freezing. There are additional “other” technologies that represent aggregate use of electricity, natural gas, and petroleum fuels to meet demands for clothes washing and drying, televisions, personal computers, office equipment, and other electrical demands. The database also contains a detailed representation of air pollutants and GHG emissions, including system-wide coverage of emission factors for CO2, NOx, SO2 and PM10.

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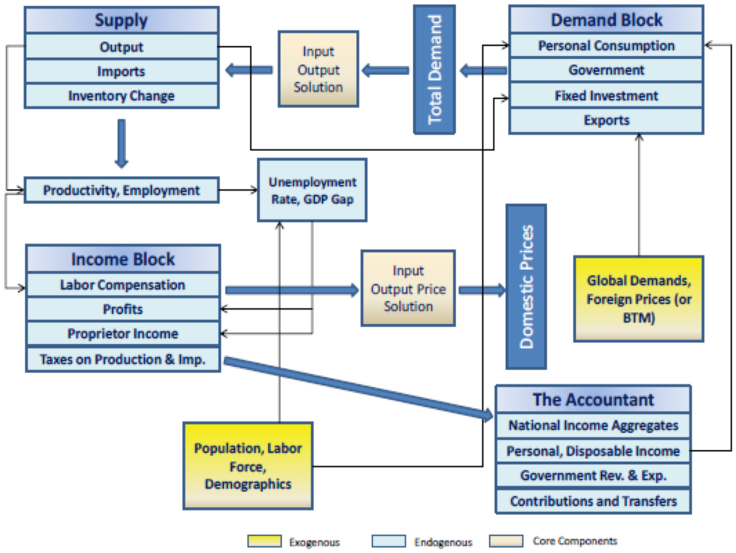
[2] For a more detailed description of this version of MARKAL see Loulou et al.,(2004).

The LIFT Model[3]

The LIFT model used for this analysis is unique among large-scale models of the U.S. economy in that it is based on an IO core and builds macroeconomic forecasts from the bottom up. Investments are made in individual firms in response to market conditions in the industries in which those firms produce and compete. Aggregate investment is simply the sum of these industry investment purchases. Decisions to hire and fire workers are made jointly with investment decisions with a view to the outlook for product demand in each industry. The net result of these hiring and firing decisions across all industries determines total employment, and hence the unemployment rate. The general structure of LIFT is shown in Figure 2.

Figure 2. Flow Diagram of the Inforum LIFT Model



Unlike typical IO frameworks, the LIFT model is dynamic, modeling changes in investment, capital stock, productivity, and prices year by year. Like other IO models, it captures spillover (indirect and induced) effects of direct expenditures. However, since LIFT is also a macroeconomic model, it adheres to budget constraints of consumers and firms, and explicitly models the federal and state and local government accounts. It also models constraints in the employment and capital markets, that may lead to "crowding-out" effects of increased investments.

Despite its IO basis, LIFT is a full macroeconomic model with more than 1,200 macroeconomic variables determined either by econometric equation, exogenously or by identity. Certain macrovariables provide important levers for studying the effects of government policy. Examples include the monetary base and the personal tax rate. Other macroeconomic variables, such as potential GDP and the associated GDP gap, provide a framework for perceiving tightness or slack in the economy.

The extensive simultaneity in LIFT requires an iterative solution for each year. At the beginning of each year's solution, first guesses are made for some important endogenous variables, such as output and prices by industry, import shares, and many macro variables. Assumptions for

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[3] See Meade (2020), McCarthy (1991). For general information on interindustry macro models developed by Inforum, see Grassini (1997) and Meade (2014). Previous studies done with the LIFT model related to the current paper include Meade, Werling and Wescott (2009), Meade (2014) and Meade and Price (2015).

exogenous variables are also established. Then the model loop runs until outputs and other variables converge.

The key steps in the model loop include determining real final demand expenditures; solving the input-output (IO) equations jointly for output, imports, and inventory change; computing employment; and finally computing prices. Final demand expenditures include personal consumption, government expenditures, exports, equipment investment, and construction investment. Personal consumption of individual products is modeled in the consumer demand system known as the Perhaps Adequate Demand System (PADS)[4]. This system allows for the classification of consumption goods into related expenditure groups, such as food, transportation or medical care. In the demand system, electricity prices affect the demand for natural gas since electricity and natural gas are substitutes in many cases. The demand system's parameters are estimated from historical consumption data. It is possible, however, to guide the level of consumption for individual products within the model. For example, if more efficient electric heat pumps are expected to come online, the amount of electricity consumed can be reduced accordingly.

With respect to supply, the IO equations in LIFT are determined by the IO coefficients, which represent the quantity of an input per unit output of a product and are specified to change over time. Individual coefficients can also be modified, to model changes in price or technology.

Jobs in the LIFT model are calculated at the industry level. There are 66 private industries and 5 government industries in the model. In the private sector, jobs are derived as a combination of real output and labor productivity projections by industry. Output is a function of final and intermediate demand by industry. Labor productivity is projected using an equation that combines a time-trend and a cyclical component. Total jobs in the economy are equal to the sum of jobs by industry and public sector jobs.

For the purposes of assessing the employment and other macroeconomic impacts associated with an economic shock, LIFT was designed to track a long-term growth path such as potential GDP, and to return to a normal rate of unemployment after a shock. The model is not constrained to immediately return to the baseline growth path, as would perhaps be true of an equilibrium or classical model. However, the model is also not Keynesian, in that eventually the model crowds out certain sectors in response to additional stimulus, and the economy starts to return to the growth path again after a response to a negative shock. In short, the goal was to design the model to be Keynesian, or demand-responsive, in the short- to medium-term, but approaching classical response in the long run.

In addition to the framework embodied in the standard LIFT model, extensions were built into the version of LIFT used in this study, that added about 600 variables that are modeled in the U.S. Department of Energy NEMS modeling system that is used to produce the *Annual Energy Projections*.

Model Coupling Methodology

The coupling between MARKAL and LIFT is described as "loose coupling", which corresponds to the idea of softlinking described by Wene (1996) and others. The aim of course is to capture insights from MARKAL on the response of the energy system, including changes to the energy mix and end-use technologies, and see how these changes interact with the broader economy as modeled in LIFT.

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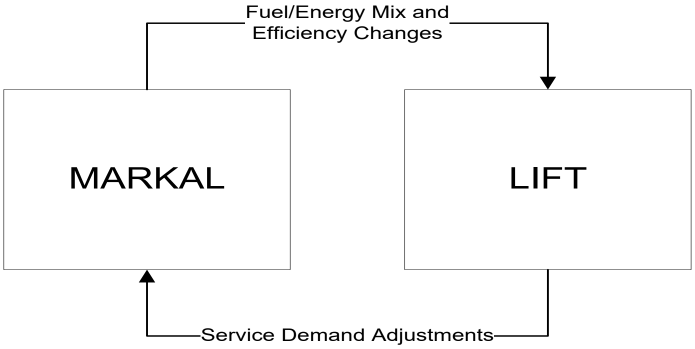
[4] See Almon (1998) for a description of PADS.

In this application, prior to the coupling, both models ran the reference case calibrated to an *Annual Energy Outlook* reference scenario. For each of the policy cases, the policy was first implemented in MARKAL and the resulting fuel mix and efficiency changes relative to the reference case were then incorporated into a LIFT policy run. The LIFT policy run therefore captures the interaction of the broader economy with the policy and energy system responses induced by the policy as measured in MARKAL. Following the LIFT policy runs energy service demands from the LIFT run were estimated and compared to the exogenous MARKAL energy service demands. For any significant deviation, the MARKAL service demands would have been adjusted and the coupling procedure repeated. The coupling dynamics are shown in Figure 3.

Figure 3. Model Coupling Methodology



The coupled model runs reveal what role various parts of the energy system and economy may play in altering energy supply and demand and reducing carbon emissions for the different policies. The MARKAL output provides insights into the opportunity for end-use efficiency improvements. It also reveals what role fuel switching may play in different parts of the energy system. The LIFT output from the coupled runs provides insight into what might happen to household income and the product mix and how these changes may alter the direct changes in energy use and emissions revealed in MARKAL.

The mechanics of the loose coupling involved developing a standard data format which could be used to pass results from LIFT to MARKAL as assumptions and vice-versa. To some extent, the process was automated by the development of routines that converted assumptions from the standard format into the native format used by each model. For example, specification of exogenous assumptions or modifications of operable equations are done using a technique called “Fixes” for the Inforum modeling system. These fixes can be applied to macroeconomic variables, sectoral variables or matrix coefficients and flows. Part of the art of linking was deriving a translation between the outputs from one model and the inputs to the other model.

Notes on the Implementation

For each of the cases the most significant responses in the energy system were limited to residential, commercial, industrial, and electric energy use. The energy system information extracted from MARKAL and incorporated into LIFT was therefore limited to these areas. For the electric sector and the end-use sectors, the MARKAL response in fuel mix and efficiency was incorporated into the LIFT policy runs. More specifically, the percentage changes in fuels used by the electric sector and fuels and electricity used by the end-use sectors observed in MARKAL were used to modify LIFT’s IO coefficients for the producing sectors and guide the energy products consumed in the consumer demand system PADS. An exception was made for the for the residential sector in the tax cases. In those cases the response in delivered energy measured in MARKAL was not used to guide PADS. Instead the response in delivered energy was determined by PADS alone. These exceptions were driven by decisions made early on when it was believed there was an important behavioral response in the tax cases that is captured (implicitly) by LIFT's consumer demand system. The decision to fully rely on PADS has led to an interesting comparison in the demand response dynamics in MARKAL and LIFT.

For all of the data that were extracted from MARKAL and incorporated into LIFT some simple smoothing techniques were applied to remove some of the volatility that is characteristic of energy optimization models.

3.2 Further Explorations with MARKAL and LIFT: The Shale Gas Revolution

Mitre and Inforum teamed up again for EMF 31 "North American Natural Gas Markets in Transition", which focused on the rapid development of "fracking" in the U.S., and the resulting sudden drop in natural gas prices.

North American gas supplies increased dramatically starting in 2006, leading to a reduction in prices, and an increase in electric power generation and industrial use. The Stanford Energy Modeling Forum (EMF) has organized several meetings to analyze the economic and climate implications of this increased natural gas supply.

The paper describes a collaborative effort between Inforum and the Mitre Corporation to use the LIFT and MARKAL models in a coupled system, to understand various implications of the shale gas revolution. Scenario analysis was again used to assess the impact of increased gas supplies on the structure of production, and on aggregate measures of well-being such as GDP and disposable income.

Some of the questions of focus for the EMF 31 study were:

- Which end-use sectors will absorb most of the increased natural gas supplies and by how much?
- Which energy sources in these sectors will be replaced by natural gas supplies?
- What is the likely range of natural gas prices at the wellhead and by end-use sector?
- How do these energy-market transformations influence carbon dioxide and other greenhouse gas emissions?
- Will North America become a major gas exporter in world markets?

The forum explored 7 common scenarios, which were implemented by a total of 15 modeling teams[5].

The full set of scenarios included:

1. *Reference case*: This case was calibrated as closely as possible to the AEO 2014 reference case.
2. *High resource case*: This case assumed faster growing U.S. shale gas and petroleum supply, with corresponding lower prices than the reference case.

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[5] This work is described in Meade (2016). The full report of EMF 31, which describes the scenarios and various modeling teams, is in Energy Modeling Forum (2015).

3. *Restricted access*: This case incorporates more pessimistic assumptions about shale supply growth, with a corresponding higher gas price.
4. *Technology performance standard*: The TPS sets a fleet average CO2 emissions rate standard across all existing and new fossil fuel generators, and allows trading of credits to achieve this standard. It is somewhat like a carbon tax in its effect, but will actually subsidize some producers who already have low carbon emissions.
5. *High international demand*: This scenario assumes increased demand for U.S. gas due to replacement of coal generation by combined-cycle gas, and adoption of natural gas vehicles.
6. *Oil-indexed pricing*: This scenario assumes that Japan and other relevant countries reduce their share of oil-indexed contracts more rapidly than in the reference case.
7. *Advanced demand*: Demand for gas will be accelerated through the introduction of aggressive expansion of ethylene production and of gas-to-liquids plants, in combination with the high supply assumed in case 2.

The Inforum / Mitre modeling team implemented all the first five of the scenarios listed above, in addition to the reference case.

As with the EMF 25 MARKAL/LIFT coupling, there were many areas where both models provided estimates of the response of a certain variable, and one or the other model's results needed to be chosen. The LIFT model was particularly valuable in expressing both negative and positive feedback relationships. In the high resource case, for example, natural gas and oil prices were assumed to be lower, and MARKAL incorporated a demand relationship based on natural gas and oil price elasticities. The LIFT model could also show the differential impacts on output prices, based partly on the share of natural gas in costs. These output prices then affected the demand for that industry's output, serving to increase fuel demand beyond what MARKAL had calculated. In cases involving efficiency improvements, the result was not only a reduction in individual input-output coefficients, but also a general multi-factor productivity improvement, which resulted in a boost to potential and actual GDP, creating additional demand for energy. This is a form of "rebound effect".

Similar issues were experienced with MARKAL as in EMF 25, where sometimes the model responded to changes in prices or assumed technological change with large and volatile movements in fuel or technology choice. For the coupling, many of these extreme changes were smoothed out. This type of volatility is often due to MARKAL's tendency to adjust quickly to changes, with no penalty imposed for too-rapid adjustment.

3.3 Net Zero by 2050

In an extensive analysis geared to examine alternative ways of the U.S. reaching “Net zero” GHG emissions by 2050, Inforum teamed with Industrial Economics and Third Way, and used the EnergyPATHWAYS model, as implemented by Evolved Energy Research.

The project[6] explored the economic implications of a possible implementation of net zero strategies and policies, that would significantly reduce greenhouse gas emissions in the U.S., which is one of the two largest contributors to GHG emissions, along with China. Net zero in the U.S. in these strategies is achieved through a combination of increased efficiency, electrification, substitution away from emitting industries, along with advanced technologies that produce low carbon fuels. Within the electric power sector, a significant realignment of generation technologies is envisioned, both to reduce reliance on fossil fuels and to reduce emissions arising from those fuels.

These strategies rely on policies to accelerate technology development and deployment, as well as to provide incentives to households, businesses and governments. These policies and technology adoption in combination may be able to reduce CO2 emissions by 80 percent by 2050. Additional GHG mitigation is achieved by reduction of other gases, and carbon removal.

Approach

To capture the full range of employment impacts associated with Net-Zero by 2050, we applied the LIFT macro-econometric interindustry model of the U.S. economy linked with the EnergyPATHWAYS model.

Based on the elements of the net-zero by 2050 pathway described above, we organize our analysis according to four broad categories, defined as follows:

- ***Power Infrastructure:*** The net-zero by 2050 technology and policy pathway involves significant increases in renewable generation capacity, battery storage installations (due to the intermittent nature of some renewables), and investment in transmission and distribution infrastructure (to integrate new renewable facilities into the grid and to accommodate increased electricity load requirements associated with electrification). In conjunction with these changes, the net-zero by 2050 pathway involves less investment in and reliance upon fossil fuel-based generating capacity.
- ***Fuels:*** To reduce GHG emissions from fuel consumption, the net-zero pathway includes increased reliance on various forms of low- and zero-carbon fuels. These fuels include SMR hydrogen (with and without CCS), electrolytic hydrogen, hydrogen produced via bioenergy carbon capture and storage (BECCS), power-to-gas, power-to-liquids, ethanol and other biofuels, ammonia, and biomass feedstocks.
- ***Energy Efficiency:*** In addition to reducing the GHG footprint of energy produced and/or consumed in the U.S., the net-zero pathway includes various investments to improve energy efficiency across the economy. These investments in energy efficiency include energy efficiency in the agricultural, commercial, residential, and manufacturing sectors. In addition, because vehicle electrification increases the efficiency of light-duty and heavy-duty vehicles, we include electric vehicles and charging infrastructure in the energy efficiency category.

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[6] See Meade and Price (2023).

- ***CO_2 Removal and Transportation:*** Finally, the net-zero by 2050 pathway involves increased reliance on technologies to capture CO_2 from the atmosphere and transport it to storage sites.

The EnergyPATHWAYS Model

The detailed implementation of changes in these four categories was first done in the ENERGYPathways model. The EnergyPATHWAYS model is a comprehensive energy accounting and analysis framework specifically designed to examine large-scale energy system transformations. It accounts for the costs and emissions associated with producing, transforming, delivering, and consuming energy in the US economy. Its strengths in infrastructure accounting and the electric power sector distinguish it from other energy models. It is well-suited for calculating the impacts of energy system decisions on infrastructure investment, emissions, and costs to energy consumers.

The model projects energy demand and costs in subsectors based on user-decisions about technology (i.e. electric vehicle adoption) and activity levels (i.e. reduced vehicle miles traveled). These projections of energy demand across energy carriers are then sent to the supply-side of the model, which calculates upstream energy flows, primary energy usage, infrastructure requirements, emissions, and costs of supplying energy. These supply-side outputs are then combined with the demand-side outputs to calculate the total energy flows, emissions, and costs of the modeled energy system.

End uses are accounted for at a high level of detail, made possible by the availability of numerous high-quality data sources for the US energy economy. Demand by end use is calculated by relating it to combinations of technology stock, service demand and energy demand. Energy technology investments on the supply side are also tracked at a detailed level, and provide for explicit descriptions of introduction of new technologies. The wear-out pattern, levelized costs, and operations cost of capital are all modeled.

There are two categories of greenhouse gas emissions in the model. First, there are physical emissions. These are traditional emissions associated with the combustion of fuels, and they represent the greenhouse gas emissions embodied in a unit of energy. Physical emissions are accounted for on the supply-side in the supply nodes where fuels are consumed, which can occur in primary, product, delivery, and conversion nodes. Emissions, or consumption, coefficients, that is the units of fuel consumed can be a subset of energy coefficients. The second type of emissions are accounting emissions. These are not associated with the consumption of energy products elsewhere in the energy system. Instead, these are a function of energy production in a node. Accounting emissions rates are commonly associated with carbon capture and sequestration supply nodes or with biomass.

The database of the United States energy economy used in the model has high geographical resolution on technology stocks; technology cost and performance; built infrastructure and resource potential as well as high temporal resolution on electricity loads by end-use as well as renewable generation profiles. EnergyPATHWAYS leverages many of the same input files used to populate the National Energy Modeling System (NEMS) used by the United States Energy Information Administration (EIA) to forecast their Annual Energy Outlook.

The U.S. energy economy is separated into 65 energy-using demand subsectors. Subsectors, like residential space heating, represent energy-use associated with the performance of an energy-service. On the supply-side, the model is separated into interconnected nodes, which are associated with the production, transformation, and delivery of energy to demand subsectors.

On the demand side, residential uses such as water heating, clothes drying, dishwashing, refrigeration, freezing, cooking, heating and lighting are modeled. Detail for the commercial sector includes water heating, ventilation, space heating, commercial lighting, commercial cooking and commercial refrigeration, among others. Demand for detailed transportation and industrial sectors are also identified.

For this study, a scenario of investments was used in the model that implemented the technologies listed above. The investment assumptions generated a spending stream for both new investment and operations and maintenance, as well as calculated changes in energy consumption for the transportation, industrial, commercial, residential and government sectors.

The EnergyPATHWAYS model calculated investment requirements for the implementation of each technology, or the costs of replacing existing equipment with more carbon-friendly technologies. The additional investment spending was used in LIFT to calculate the jobs and output impacts of the investments. In addition, intermediate input-output coefficient changes were implemented in LIFT based on energy consumption results from PATHWAYS.

4. Summary and Conclusions

The marriage of energy systems models (ESMs) with economic models appears to be a lasting one, with a roughly 50 year history. The linking of separate models still appears to be the most common approach. The logic of model building often conspires to encourage specialization, with energy economists, macro economists, CGE models and input-output modelers all having their own focus.

The benefits of this marriage are many. Updating and maintaining the separate models is less costly than maintaining a large integrated model. Furthermore, testing components of the model in isolation from an economic model is more straightforward. The ESM can explore the relative costs and benefits of competing technologies to satisfy a given end use, given economic drivers such as end use demand, costs of fuels, materials and components, labor costs and cost of capital, which may all be derived from a suitable economic model. In return, the ESM can supply information on input demand, labor requirements and supply costs for end uses to the economic model. The ESM can also be used to draw conclusions about investment requirements necessary to implement new technologies, which can be input to the economic model to inform forecasts of investment expenditures.

The pitfalls also are many. The translation of concepts from the energy systems model to the economic model and back are often imprecise. The economic model will most likely be working in monetary units only, whereas the ESM may speak in terms of Petajoules, Btus, Kwh, gallons or liters of fuel, or square feet of buildings. These can be converted using ratios or regression analysis, but there are still difficulties in meaning and interpretations. For example, in an input-output model, electricity is a homogenous commodity, and is sold in various markets as indicated by the IO table. However, in an ESM, electricity prices will vary according to whether the customer is commercial, industrial or household. The ESM will also pay more attention to the question of transmission and distribution, and electricity losses, on which the IO or economic model is agnostic.

There are many areas where the two models will find overlap, or where they will show conflicting results. For example, and economic model such as LIFT will model personal consumption of many different products and services, including gasoline, electricity and natural gas, as part of a comprehensive demand system based on per capita real income, and relative prices between different consumption categories. The ESM will calculate household natural gas and electricity demand based on the types of equipment used for heating, cooling, washing and drying, refrigeration, etc., as well as the projected energy efficiencies of each type of equipment. Similarly motor vehicle fuel demand will be calculated in the ESM based on relative fleet sizes of different types of vehicles, and their efficiencies, as well as vehicle miles traveled (VMT). Given that the ESM has a reliable set of economic drivers as inputs, one may argue that the ESM calculation for household gasoline, electricity and natural gas makes use of better information than the economic model. However, almost all of the ESMs solve by optimizing an objective function, and the resulting forecasts can often be quite discontinuous and volatile. To communicate better with the economic model, the ESM may need to have inertia or adjustment costs explicitly incorporated. In our experience linking with MARKAL and EnergyPATHWAYS, this is often not the case, and we need to have a dialog with the energy modelers on how to relieve these discontinuities.

Communication between the different types of modeling groups continues to be lively, and this bodes well for future improvements in both the models and the methods of linking. The availability of open source ESMs is intriguing. Perhaps we may also see some open source economic models becoming available in the next decade.

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Appendix A

Table A-1. Energy Systems Models

Model Name	**Descriptor**	Maintainer	Website
PRIMES	Price-induced Market Equilibrium System	E3Modeling, Technical University of Athens	https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-primes/
REMix	Renewable Energy Mix	Institute of Networked Energy Systems	https://www.dlr.de/en/ve/about-us/departments/energy-systems-analysis
METIS	Energy system modelling software for the European electricity, gas, heat and hydrogen sectors.	European Commission	https://energy.ec.europa.eu/data-and-analysis/energy-modelling/metis_en
OSeMOSYS	Open Source Energy Modelling System	OSeMOSYS Community	http://www.osemosys.org/
SimREN	Simulation of Renewable Energy Networks	EnergyPLAN	https://www.energyplan.eu/othertools/national/simren/
NEMS	National Energy Modelling System	US DOE EIA	https://www.eia.gov/outlooks/aeo/nems/documentation/
POLES	Prospective Outlook on Long-term Energy Systems	Enerdata	https://www.enerdata.net/solutions/poles-model.html
OPERA	High-Resolution Energy System Model for Sector Integration Research		
IWES	Integrated Whole Energy System	Frauenhofer Institute	https://www.iwes.fraunhofer.de/en.html
ESME	Energy System Modelling Environment	Catapault Energy Systems	https://es.catapult.org.uk/tools-and-labs/our-national-net-zero-toolkit/energy-system-modelling-environment/
ETM	Energy Transition Model	Quintel	https://energytransitionmodel.com/
LEAP	Low Emissions Analysis Platform	SEI	https://www.sei.org/tools/leap-long-range-energy-alternatives-planning-system/
IKARUS	Dynamical bottom-up linear cost-optimization scenario model for national energy-systems	Institute of Energy Research	
PATHWAYS	Identifies GHG reduction measures from transportation, buildings, industry, electricity, and other sectors	Energy+Environmental Economics (E3)	https://www.ethree.com/tools/pathways-model/