Perspectives on the Validation of Energy System Models

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July 9, 2011

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With acknowledgement and appreciation to the dedicated energy-economic systems analysts at the National Center for Analysis of Energy Systems at BNL (an ERDA-designated Center, circa 1975) who were responsible for aspects of the modeling that went right!

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Motivation for Energy Modeling and Retrospective Validation

- **Numerous energy-economic models are being applied to long term "forecasting" to 2030 for energy technology planning, and as far as 2100 for climate change analyses. <u>Policy makers and analysts in 2011 need evidence of the applicability and value of current energy system and economic models for R&D technology planning</u>**
- **This paper is a retrospective validation of a predecessor model, the Reference Energy System (RES)* and Brookhaven Energy System Optimization Model (BESOM) that was applied in 1975 to develop projections to the Year 2000** (a much less robust predecessor of the current MARKAL/TIMES Energy Model***)**
- **Retrospection also provides insights and lessons from the Energy Crisis I of the 70's to the present déjà vu experience**

*** Kenneth C. Hoffman, The U.S. Energy System: A Unified Planning Framework, Energy Modeling, Resources for the Future, Washington, DC (M. Searl, Ed) pp. 108-43, 1973**
**** A National Plan for Energy Research, Development, and Demonstration: Creating Energy Choices for the Future, ERDA-48, June 28, 1975**
***** Carol Shay, et al, EPA US MARKAL Database Documentation, EPA-600/R-06/057, February 2006. Also see Gary Goldstein at http://www.etsap.org/index.asp**

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Model Verification and Validation

- Model verification is often defined as "ensuring that the computer program of the computerized model and its implementation are correct" (Sargent 2010)
- Model validation is usually defined to mean "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Sargent, 2010)

Validation is the greater challenge and dependent on the specific purposes of the long term analytics. Descriptive, Normative/Prescriptive, and Predictive objectives each pose different validation criteria. Too often emphasis is placed on predictive capability when the intent and value is elsewhere.
- Widespread usage of MARKAL & LIFT over decades is clearly a market "validation" -

Robert G. Sargent, et al, Verification and Validation of Simulation Models, Proceedings of the 2010 Winter Simulation Conference

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Validation and Verification Challenge

Objective	Validation	Verification
Descriptive		
Normative		
Predictive		

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Retrospective Validation Case Study: Objectives of 25 year projections to Year 2000

US, 1975, National Center for Analysis of Energy Systems, Brookhaven National Laboratory (BNL)

- **Provide a presentation framework and project the impact of the ERDA R&D Plan**
  - **A National Plan for Energy Research, Development, and Demonstration: Creating Energy Choices for the Future, ERDA-48, 1975**
- **Define R&D objectives and potential impacts for energy supply and end use technologies**
  - **Required a long-term model to at least 2000 given the life cycle of energy R&D programs (extended to 2020 to represent fusion)**

Pakistan, 1983, for International Energy Development Corporation (IEDC) engagement with the Ministry of Planning

- **Develop a projection of PakIstan's energy future for their 5-Year Economic Plan (80% of which were energy investments)**
- **Provide a long term energy plan that satisfied World Bank and US-AID criteria for assistance, and that would attract private sector investment**

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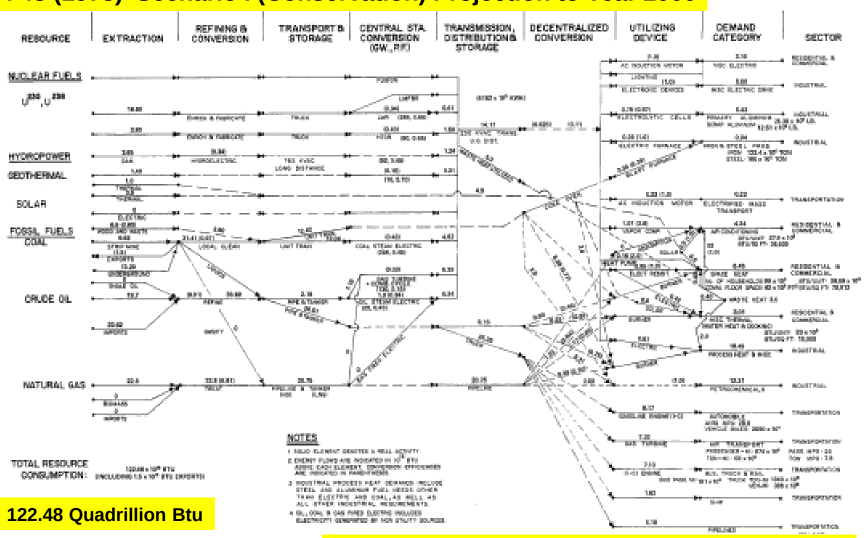
RES Level of Detail, 1975

ERDA-48 (1975) Scenario I (Conservation) Projection to Year 2000



122.48 Quadrillion Btu

Energy Services were emphasized to focus equal attention to improving end use efficiency. Service levels were aligned with macro models, later these were fully integrated

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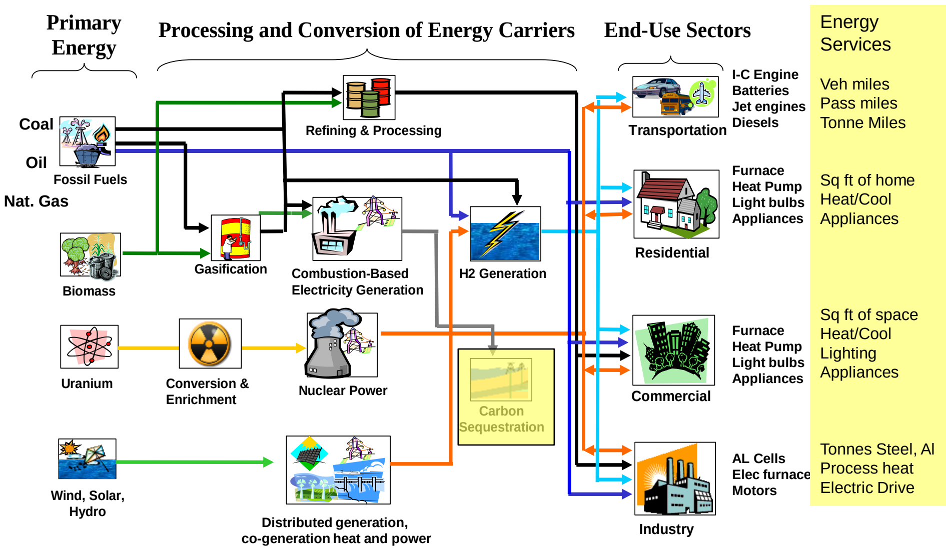
The Reference Energy System (RES) & BESOM, 1975

(RES Version: EPA MARKAL Team, Office of Research and Development, Dan Loughlin)



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The Energy Situation, circa 1970's

Some Policy Controversies (& Follies) that were better informed by the modeling (déjà vu all over again)

- Energy is essential to modern society, employment, and our lifestyle, so:
  - Demand must continue to grow at historical annual rates, 3% for total energy resources (~200 Quads in 2000) and 7% for electric
  - Policy aimed at "Joe & Jill Sixpack"
- Natural gas prices must be regulated as there will be no additional supply at higher prices (led several years later to "ERDAgate")
- Prediction of an impending "Hubbert Peak" for oil
- The Fast Breeder Reactor is needed early to produce Pu, because supplies of low cost Uranium are limited
  - A Plutonium Standard is superior to a gold standard as representative of the real industrial strength of a nation
- "Drain Arabia first" may have been a viable energy policy, but we now need to be independent of foreign oil
- Technology will come to our rescue

Note: Existing models were generally fuel & electric-sector specific; RES/BESOM was the state-of-the-art comprehensive all-resource "supply chain" technology model of the "energy system" that incorporated end use detail
  - In addition to producing realistic projections, the model captured descriptive inter-relationships that clarified and corrected several of the above perceptions

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Retrospective Validation, US Energy Projection Circa 1975

- Developed 5 Technology Scenario projections to the Year 2000
- Scenario I, Conservation, was felt to be the most likely by the analytical team and is addressed here. Purpose of incorporating Energy Services concept in all cases was to deal with end-use demand efficiency consistently with energy supply

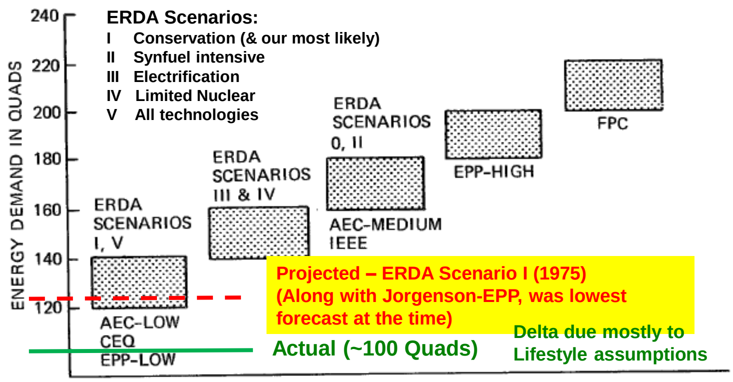


Figure B–14. Estimated U.S. Energy Demand, Year 2000

A National Plan for Energy Research, Development, and Demonstration: Creating Energy Choices for the Future, ERDA-48, June 28, 1975, page B-22

How reliable are long term forecasts as a planning tool? In 1975 We Developed a Projection for the U.S. to 2000

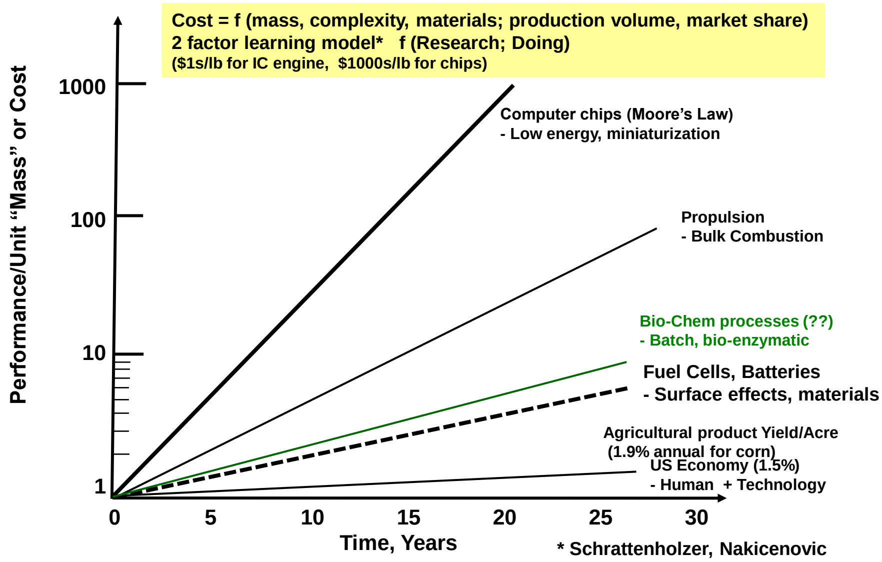
Base Year & Projection:	1974 Base year (Actual)	2000 Projection* (Done in 1975)	2000 Actual**
TOTAL Energy, Quads (10E15 Btu)	73	122	100
Domestic Supply			
Oil	23	20	12 (5.8 MM bbl/d)
Gas	22	23	20 (19.4 Tcf)
Coal	14	22	24
Nuclear	1	20	7
Hydro, Geo, Solar	3	17	6.3
Imports, Oil	10	20	30
Elec. Power, Peak Gw	400	875	811
Energy, T kwh	1.85	4.1	3.6
Cost, 2000 $/Million Btu	3.50	7.00	5 - 12
CO2, Billion Tonnes		6.3	5.9
Auto, Billion Vehicle Miles		2050	1600
MPG		28	21
Air, B Pass. Miles		0.8	0.53
		*ERDA-48	**DOE-EIA Outlook

"Game Changing" Technologies for Year 2k
BESOM Normative Indication of value, but not in projection
(Informal 1975 request for a "Top 5" R&D target list)

- 300 mile range battery for electric vehicle
  - Displace oil, level load curve with overnight charge
- High power density fuel cell for distributed power generation
  - Natural Gas/Hydrogen option
- Ground-coupled heat pump
  - Super high efficiency for electrification – heating and cooling
- Coal liquefaction
  - Displace imported oil
- Hydrogen storage, low-mass hydrides (Mg, Al, Li)
  - Enable hydrogen economy as "backstop technology"

Noted that there were numerous base-load power generation options for the plan, but a primary need for electrification enablers and high energy-density portable fuels"

Technology Trends – Last 25 years
Moore's Law Analogues for Energy Technologies



* Schrattenholzer, Nakicenovic

How reliable are long term forecasts as a planning tool? In 1983 We Developed a Projection for Pakistan to 2003 (Incorporated income and service demand elasticities)

Base Year & Projection:	1981 Base year (Actual)	2003 Projection (Done in 1983)	2004 "Actual" (E)** MTOE (Source Units)
TOTAL Energy, MTOE (Million Tonnes Oil Equiv.)	*24.0*	59	
Nominal, Commercial	15.6	55.4	50 (~2 Quads)
Policy minimum		51.6	
Domestic Supply			
Oil	0.5	3-6	3 (59.4 kbbl/day)
Gas	6.5	15-21	22 (968 Bcf)
Coal	1.1	6-12	2 (3.5 M sh. Tons)
Hydro, other	2.2	14-17	8 (16% of Total)
Non-commercial	*8.4*	14	Not reported
Imports, Oil	5.3	17-0	15 (290 kbbl/d)
Elec. Power, Peak GW	6.0	17-25	20
Energy, B kwh	26	74-110	80.2
		*IEDC Report, p 95, 97 (Based on RES/BESOM)	**DOE-EIA 2004 country profile, converted to MTOE using RES Conversion factors

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Proven Strengths of MARKAL Predecessors

- Normative/Prescriptive power of least cost capacity management logic applied to the entire energy system
- Ability to apply with perfect foresight or the more realistic myopic incremental approach with ever changing long term outlooks
- Ability to regionalize the model
- Ever increasing menu of end-use technologies that govern technical efficiency and inter-fuel substitution
- Ability to separate role of end-use technologies for increased efficiency and socio-economic factors that influence the demand for energy services
- Time slices that capture load curves for electric power
  - More detail is required for variable sources and storage technologies

MIT Energy Lab Report on "Energy Demand in the ERDA Plan", 8/6/75, p 10:

"The significant contribution of the RES is to force complete internal consistency in developing and presenting forecasts of future energy systems." p 10.

Also Identified several BESOM deficiencies with constructive recommendations that led to its further evolution – e.g. better energy services data, and coupling with Hudson-Jorgenson Model of the US economy.

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RES/BESOM Validation Summary – for Year 2000 Projections and their Intended Purposes

Objective	Validation	Verification
Descriptive	✓	✓
Normative	✓	✓
Predictive (Highly Conditional, If-then analysis)	✓	✓

Validation of these primitive predecessors of MARKAL/TIMES/TIAM indicates an acceptable lower bound on the validity of those much more comprehensive and robust models

Still many challenges given the ever increasing scope, timeframe, and intended purposes of modeling

Future Evolution to Improve Descriptive, Normative, (and Predictive) Power

- Stochastic formulations?
  - Concepts surpass ability to quantify parameters for long term
  - Current sensitivity analyses capabilities are acceptable, if not always performed
  - Transparency and visualization methods are more important for policy-makers
- Data Needs & Technology Characterizations?
  - Rather than modeling around existing data sets (looking under the lamp-post), modeling of complex systems must propose and analyze new data needs
  - Learning curves must evolve to include closer coupling to R&D challenges, plans, and basic technical principles
- Multi-scale/domain coupling?
  - Coupling of technology models with inter-industry and macro-economic and financial models is important and well underway
  - Behavioral modules will augment economic content, e.g. investment decisions, market dynamics, demand response to real time pricing and policies
  - Atmospheric chemistry, land use, oceanography, and ecological modules will be improved to better address Carbon mitigation policies
  - More attention will be given to comparative economics of adaptation strategies re climate change (Geo-engineering anyone?)
  - Loose coupling of "integrated" models can provide greater visibility into complex system interactions and provide for more thoughtful treatment of uncertainties

Backup Charts

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Summary Validation of RES and BESOM
Compared long term Forecasts to year 2000 with Actual

While the models were designed for descriptive (what's possible?) and normative (what's best?) purposes, they also provided reasonable predictive (what will be?) capabilities. Validation may be summarized at each of these 3 levels:

- Descriptive
  - The RES and BESOM provided a rich description of existing and emerging technologies to be selected to meet normative objectives, and identified data gaps and needs that were not being met by agencies
  - The descriptive details covering supply and end use allowed different normative strategies to be addressed with specific standards and detail
  - Descriptive detail facilitated retrospective analyses at a level of attribution not possible with more aggregate models
- Normative/Prescriptive
  - Use of LP methods allowed specific expression of normative objectives and realistic constraints expressing policy options of interest at the time, several which were close to future policies that emerged.
  - Applied utility least-cost capacity expansion method to the overall energy system (cost minimization ~ profit maximization) and incorporated carbon and other emission constraints
- Predictive
  - Policy constraints (e.g. "lifestyle maintenance" through inelastic demand for energy services) along with emergent behaviors in response to policy (e.g. SVU phenomena) had a strong influence on forecasting accuracy
  - Aggregate projections had stronger predictive capabilities, confirming the "Hogan Rule" – model at a level of detail (regional or technical) finer than the level to be predicted
  - When forced to stand behind an analysis as a "forecast", always couched it in "highly conditioned" terms

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Ken Hoffman Bio

Ken is a Senior Principal Consultant at The MITRE Corporation's Center for Connected Government and earned a Ph.D. in Systems Engineering from the Polytechnic Institute of Brooklyn.

Dr. Hoffman was Director of the (ERDA-designated) National Center for Analysis of Energy Systems at Brookhaven National Laboratory in the 1970's and led the development of the Reference Energy System and Brookhaven Energy System Optimization Model. He initiated the development work on MARKAL in collaboration with KFA-Juelich. In that era he also played an advisory role for the National Academy of Sciences in the early stages of IIASA'a energy program, and consulted with Systems Europe in Brussels on the development of energy models for the European Commission and with the International Energy Development Corporation in Geneva.

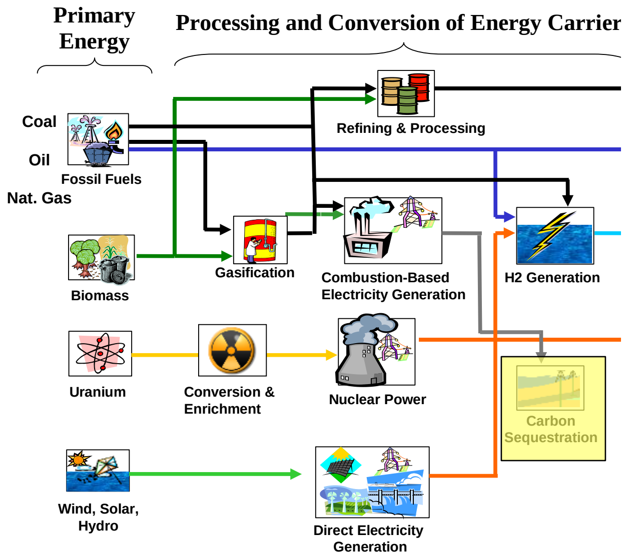
In addition to work on energy-economic modeling, he managed energy R&D and was project engineer for the Brookhaven Solar Neutrino Observatory.

His career path from Brookhaven included executive management positions at the Mathematica Corporation (1980-85) and Martin Marietta (1985-90), then to his current position at The MITRE Corporation (a not for profit organization that operates five FFRDCs).

Largest RES ever, April 5, 1974
Phil Palmedo & Ken Hoffman

Energy Supply Models, 1970's

RES per Ozge Kaplan, EPA



Energy Demand

Fuel oil, Gasoline
Biofuels

Natural Gas

Hydrogen

Electric Power

Demands modeled with Fuel-specific Own Easticities

Cross-elaticities of substitution across fuels and electricity

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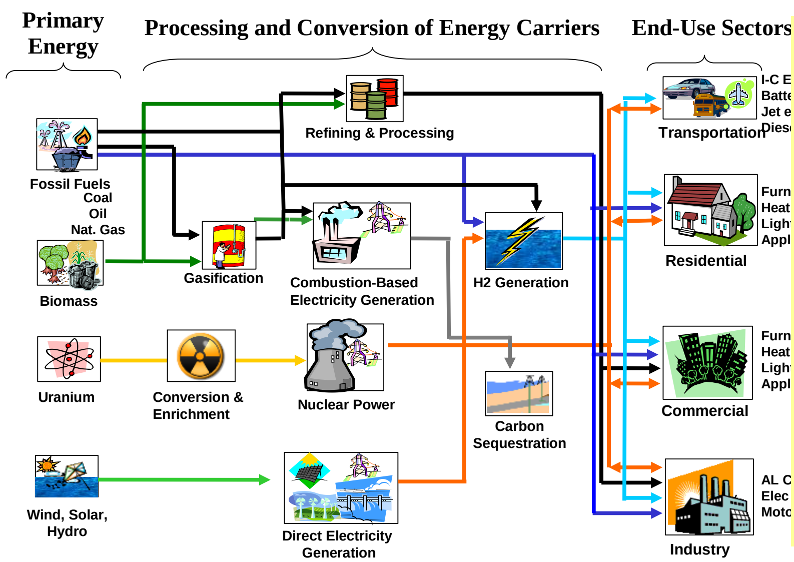
The Energy System 2010

MARKAL (IEA, DOE – BNL, and EPA), TIMES, DOE/EIA-NEMS, TIAM, JGCRI-GCAM



Service Demand

Veh miles
Pass miles
Tonne Miles

Sq ft of home
Heat/Cool
Appliances

Sq ft of space
Heat/Cool
Lighting
Appliances

Tonnes Steel, Al
Process heat
Electric Drive

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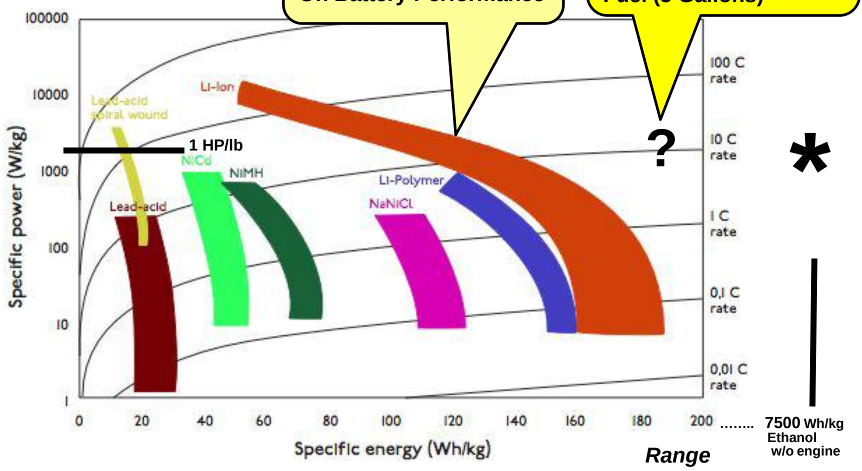
Technology Characterization
Ragone Chart for Battery Storage

Impacts of Nanomaterial Surfaces & Catalysts On Battery Performance

300 mile range Unitary Battery/Fuel Cell with Direct Methanol Fuel (5 Gallons)

Acceleration



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Stanford EMF-25 Energy Demand & Tax Policies

MITRE applied MARKAL with Energy Tax, Subsidy and Incentive Submodule

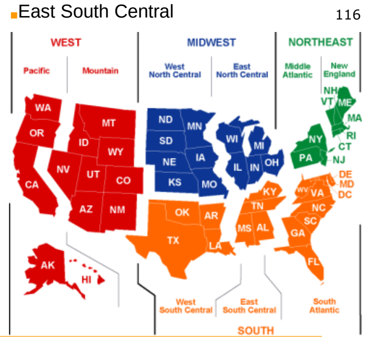
2,040 taxes, subsidies, Federal and State Incentives (e.g.: rebates, grants, and loans**)**

Definitional Elements	**Organizational Elements**
Name	Primary Energy
Description	Conversion
Tax Rate	Distribution
Map to Energy System	End Use Devices
Expiration Date	Demand for Energy Supply
Source	
Tax Incentive Type	

	Federal	**State**	**Total**
Primary Energy Supply	22	169	191
Conversion	32	210	242
Distribution	15	71	86
End Use Devices	23	1469	1492
Demand for Energy Supply	5	24	29
Totals	**97**	**1943**	**2040**

Regional Detail (Census Regions):

Pacific	336
West North Central	273
South Atlantic	263
East North Central	241
Mountain	236
New England	194
West South Central	155
Mid Atlantic	129
East South Central	116



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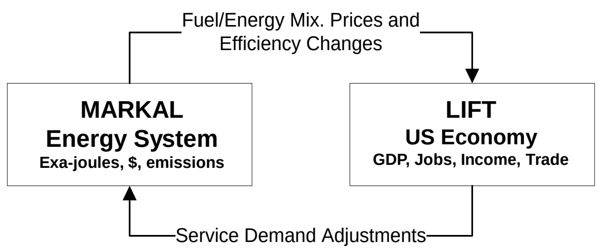
Coupling the Energy System & Economy Steckley, et al (2010)



- **Adjusted LIFT's IO coefficients to incorporate MARKAL output**
- **In the residential sector relied on LIFT's consumption model when possible**
- **Estimated service demands in LIFT and iterated if significant change**