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Motivation

1. California’s energy and climate policies
   - AB32 (cap-and-trade, 1990 levels by 2020, LCFS, RPS)
   - 2050 “target” = 80% reduction by 2050

2. Lack of existing models

3. Build on previous UCD research
   - e.g., 80in50 studies; alternative fuels infrastructure development
The CA-TIMES Model

- **Funded by the California Air Resources Board (2010 - 2012)**
- CA-TIMES (The Integrated MARKAL-EFOM1 System) model is an Energy–Economy–Environment (3E) model for the California energy system.
- **Marked improvement over current statewide energy modeling tools for CA**
- **Model covers all sectors of the California energy system (not Rest of World)**
  - Primary energy resource extraction, imports/exports, electricity production, fuel conversion (e.g., refineries), and the residential, commercial, industrial, transportation, and agricultural end-use sectors
  - The model is a set of MS Excel data files that fully describes the underlying energy system (technologies, commodities, resources and demands for energy services).
  - MARKAL and TIMES are model “shells”. We tailor the model to CA – thus, data driven.
  - Hundreds to thousands of technologies and commodities
- Depicts production, trade, transformation and use of energy and materials, and associated emissions, as a Reference Energy System (RES) network.
- Identifies most cost-effective pattern of resource use and technology deployment over time under policy, social and resource constraints.

Primary and Secondary Energy Supply

- **Resource supply curves**
  - In-State: oil, coal, natural gas, biomass (12 types), biogas
  - Imports (from RUS or ROW): oil, coal, natural gas, LNG, uranium, refined products, biomass (8 types), biofuels, synfuels, hydrogen, electricity
- **Flexible refinery**
  - Produces reformulated gasoline, diesel (ultra low-sulfur), distillate, jet fuel, kerosene, LPG, residual fuel oil, methanol, petroleum feedstocks, petroleum coke, and asphalt
Primary and Secondary Energy Supply

• Fuel conversion technologies
  ▪ Cellulosic ethanol plants (bio- and thermo-chemical), Biodiesel, Bio-oil (via pyrolysis)
  ▪ Synthetic fuels (FT poly-generation plants producing gasoline, diesel, jet fuel, and electricity from coal and/or biomass, w/ and w/o CCS)
  ▪ Hydrogen (coal gasification, natural gas SMR, biomass gas., water electrolysis) – variable plant sizes and delivery methods

• CCS
  ▪ High-, Medium-, and Low-flow pipelines

Primary and Secondary Energy Supply

• Electric generation
  ▪ Natural gas (gas turbine, steam turb., combined-cycle)
  ▪ Coal (steam turbine and IGCC)
  ▪ Oil (steam turbine)
  ▪ Biomass (steam turbine and IGCC)
  ▪ Wind (on- and off-shore, multiple wind class regions)
  ▪ Solar (centralized solar thermal, PV)
  ▪ Nuclear (light water reactor, pebble-bed modular reactor, gas-turbine modular helium reactor)
  ▪ Other renewables (hydro, geothermal, H2 fuel cell, tidal/ocean)
  ▪ Bio-gas (from landfills and animal waste digesters)
Novel Research Questions – Improved Timeslice Resolution

• Demand timeslices
  ▪ Applied to electricity demands in residential, commercial, industrial, agricultural, and transport

• Supply timeslices (availabilities)
  ▪ Applied to fossil, nuclear, and renewable power plants
  ▪ Availability factor (capacity factor) is limited within each timeslice (i.e., max % of installed capacity is available)
  ▪ Historical plant timeslice data comes from a dispatch model for California, EDGE-CA (McCarthy and Yang, 2009)

• How will the transportation sector of the future interact with other sectors, namely electricity production, from which it is now largely separate?
  ▪ electric vehicle re-charging, intermittent renewables

Time-of-Day Electricity Demand, Renewable Elec. Supply, and EV Re-Charging Scenarios

Source: McCarthy and Yang, 2009, University of California, Davis
### Novel Research Questions – Improved Timeslice Resolution

<table>
<thead>
<tr>
<th>Total ELC Demand (share of year)</th>
<th>T1 0:00 –&gt; 3:00</th>
<th>T2 3:00 –&gt; 6:00</th>
<th>T3 6:00 –&gt; 9:00</th>
<th>T4 9:00 –&gt; 12:00</th>
<th>T5 12:00 –&gt; 15:00</th>
<th>T6 15:00 –&gt; 18:00</th>
<th>T7 18:00 –&gt; 21:00</th>
<th>T8 21:00 –&gt; 24:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan/Feb</td>
<td>1.4%</td>
<td>1.3%</td>
<td>1.9%</td>
<td>2.1%</td>
<td>2.0%</td>
<td>2.1%</td>
<td>2.2%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Mar/Apr</td>
<td>1.5%</td>
<td>1.3%</td>
<td>1.9%</td>
<td>2.1%</td>
<td>2.2%</td>
<td>2.0%</td>
<td>2.2%</td>
<td>2.5%</td>
</tr>
<tr>
<td>May/Jun</td>
<td>1.6%</td>
<td>1.4%</td>
<td>2.0%</td>
<td>2.3%</td>
<td>2.4%</td>
<td>2.4%</td>
<td>2.3%</td>
<td>2.6%</td>
</tr>
<tr>
<td>Jul/Aug</td>
<td>1.8%</td>
<td>1.8%</td>
<td>2.2%</td>
<td>2.7%</td>
<td>3.0%</td>
<td>3.1%</td>
<td>2.8%</td>
<td>2.3%</td>
</tr>
<tr>
<td>Sep/Oct</td>
<td>1.6%</td>
<td>1.7%</td>
<td>2.1%</td>
<td>2.4%</td>
<td>2.5%</td>
<td>2.7%</td>
<td>2.5%</td>
<td>2.6%</td>
</tr>
<tr>
<td>Nov/Dec</td>
<td>1.6%</td>
<td>1.6%</td>
<td>1.8%</td>
<td>2.2%</td>
<td>2.2%</td>
<td>2.2%</td>
<td>2.4%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

### Wind Speeds (m/s)

| Jan/Feb                         | 5.3 | 5.2 | 5.0 | 4.9 | 5.2 | 5.1 | 5.2 | 5.4 |
| Mar/Apr                         | 5.3 | 8.4 | 7.4 | 6.7 | 7.3 | 8.4 | 5.3 | 9.3 |
| May/Jun                         | 10.5| 9.7 | 8.5 | 7.7 | 8.2 | 9.6 | 10.7| 10.7|
| Jul/Aug                         | 9.9 | 8.6 | 7.1 | 5.9 | 6.9 | 8.9 | 9.9 | 11.6|
| Sep/Oct                         | 6.3 | 6.3 | 5.6 | 4.9 | 5.5 | 6.1 | 6.6 | 7.2 |
| Nov/Dec                         | 5.3 | 5.7 | 5.1 | 4.9 | 5.5 | 5.6 | 6.1 | 6.1 |

### Solar Insolation (W/m²)

| Jan/Feb                         | 0.0 | 0.0 | 3.29 | 6.18 | 6.09 | 2.46 | 0.0 | 0.0 |
| Mar/Apr                         | 0.0 | 23.7| 530.8| 723.5| 833.5| 422.8| 0.0 | 0.0 |
| May/Jun                         | 0.0 | 111.4| 681.0| 791.0| 781.3| 581.3| 50.0| 0.0 |
| Jul/Aug                         | 0.0 | 80.0 | 619.9| 795.6| 755.2| 535.0| 39.2| 0.0 |
| Sep/Oct                         | 0.0 | 11.2 | 504.1| 705.5| 714.7| 352.3| 0.0 | 0.0 |
| Nov/Dec                         | 0.0 | 0.0 | 377.4| 797.1| 723.6| 234.3| 0.0 | 0.0 |

Source: McCarthy and Yang, 2009, University of California, Davis

### Transportation End-Use Sector

<table>
<thead>
<tr>
<th>Subsectors</th>
<th>Classes</th>
<th>Technology and Fuel Types</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-duty Cars</td>
<td>---</td>
<td>Gasoline, Diesel, HEV, Ethanol Flex Fuel, Natural Gas, LPG, PHEV 10/30/40/60, BEV, H2FCV</td>
<td>VMT</td>
</tr>
<tr>
<td>Light-duty Trucks</td>
<td>---</td>
<td>Gasoline, Diesel, HEV, Ethanol Flex Fuel, Natural Gas, LPG, PHEV 10/30/40/60, BEV, H2FCV</td>
<td>VMT</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>---</td>
<td>Gasoline</td>
<td>VMT</td>
</tr>
<tr>
<td>Medium-duty Trucks</td>
<td>---</td>
<td>Gasoline, Diesel, HEV, Natural Gas, LPG, PHEV 10/30/40/60, BEV, H2FCV</td>
<td>VMT</td>
</tr>
<tr>
<td>Heavy-duty Trucks</td>
<td>---</td>
<td>Gasoline, Diesel, High-eff. Diesel, Natural Gas, LPG</td>
<td>VMT</td>
</tr>
<tr>
<td>Buses</td>
<td>Transit, School, Intercity</td>
<td>Gasoline, Diesel, High-eff., HEV, Natural Gas, LPG, PHEV 10/30/40/60, BEV, H2FCV</td>
<td>VMT</td>
</tr>
<tr>
<td>Rail</td>
<td>Light, Heavy, Commuter, Intercity, Freight</td>
<td>Diesel, Electricity</td>
<td>PMT, TMT, PJ</td>
</tr>
<tr>
<td>Marine</td>
<td>Harbor craft, Large Vessels, Personal boats</td>
<td>Gasoline, Diesel, Ethanol, Residual Fuel Oil, Diesel MC Fuel Cell</td>
<td>TMT, Hours</td>
</tr>
<tr>
<td>Aviation</td>
<td>Passenger, Freight, General</td>
<td>Jet fuel, Aviation Gasoline, Hydrogen</td>
<td>PMT, TMT, Hours, PJ</td>
</tr>
<tr>
<td>Off-road and Construction</td>
<td>---</td>
<td>Gasoline, Diesel, Natural Gas, LPG, Ethanol, Hydrogen, Electricity</td>
<td>Hours</td>
</tr>
<tr>
<td>Agriculture</td>
<td>---</td>
<td>Gasoline, Diesel, Ethanol, Hydrogen, Electricity</td>
<td>Hours</td>
</tr>
<tr>
<td>Pipelines</td>
<td>---</td>
<td>Natural Gas</td>
<td>PJ</td>
</tr>
</tbody>
</table>
Novel Research Questions - Transportation

- Transport and electric sector interactions

- Can behavioral aspects be brought into an energy systems models?
  - transport mode-switching, vehicle preferences (light-duty cars vs. trucks), land use planning policies (VMT reduction)
  - short- vs. long-term demand elasticities
  - differentiated hurdle rates by transport technology-fuel type

Residential Sector

- Two housing types: single-family and multi-family
- Demand drivers: appliance saturation rate, housing size, and housing heating/cooling coefficient
Commercial Sector

- Each commercial building type has a constant end-use energy service demand per unit of floorspace (with elasticity)
- Floorspace is projected exogenously to 2050

### Building Types

<table>
<thead>
<tr>
<th>Building Types</th>
<th>Energy Services</th>
<th>Technologies</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colleges</td>
<td>Cooling</td>
<td>Heat Pumps, Chillers, AC</td>
<td>PJ</td>
</tr>
<tr>
<td>Food Stores</td>
<td>Heating</td>
<td>Heat Pumps, Boilers, Furnace, Gas and Electric</td>
<td>PJ</td>
</tr>
<tr>
<td>Hospitals</td>
<td>Lighting</td>
<td>Incandescent, CFL, T12, T8, SSL</td>
<td>Lumens</td>
</tr>
<tr>
<td>Hotel/Motel</td>
<td>Office Equipment</td>
<td>--</td>
<td>PJ</td>
</tr>
<tr>
<td>Large Offices</td>
<td>Cooking</td>
<td>Gas and Electric Range, Induction</td>
<td>PJ</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Refrigeration</td>
<td>Refrigerator, Walk-in</td>
<td>PJ</td>
</tr>
<tr>
<td>Restaurants</td>
<td>Ventilation</td>
<td>CAV, VAV</td>
<td>CFM</td>
</tr>
<tr>
<td>Retail</td>
<td>Water Heating</td>
<td>Solar, Electric, Gas, Heat Pump, Tank and Instantaneous</td>
<td>PJ</td>
</tr>
<tr>
<td>Refrigerated</td>
<td>Misc</td>
<td>--</td>
<td>PJ</td>
</tr>
<tr>
<td>Warehouse</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Energy Services

- **Cooling**: Heat Pumps, Chillers, AC
- **Heating**: Heat Pumps, Boilers, Furnace, Gas and Electric
- **Lighting**: Incandescent, CFL, T12, T8, SSL
- **Office Equipment**: --
- **Cooking**: Gas and Electric Range, Induction
- **Refrigeration**: Refrigerator, Walk-in
- **Ventilation**: CAV, VAV
- **Water Heating**: Solar, Electric, Gas, Heat Pump, Tank and Instantaneous
- **Misc**: --

### Industrial Sector

- Petroleum refining, oil and gas extraction, and food processing are the largest consumers of energy.
- CHP systems are widely utilized in oil extraction, petroleum refining, and food processing.

### Industries

<table>
<thead>
<tr>
<th>Industries</th>
<th>Energy Services</th>
<th>Fuel Types</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum Refining</td>
<td>Conventional Boiler</td>
<td>Natural Gas, Coal, Distillate, Residual Fuel Oil, LPG, Electricity</td>
<td>PJ</td>
</tr>
<tr>
<td>Oil &amp; Gas Extraction</td>
<td>CHP and/or Cogeneration</td>
<td>Natural Gas, Coal, Biomass, Waste, Distillate, Residual Fuel Oil</td>
<td>PJ</td>
</tr>
<tr>
<td>Food Processing</td>
<td>Process Heating</td>
<td>Natural Gas, Coal, Electricity, LPG, Distillate, Residual Fuel Oil</td>
<td>PJ</td>
</tr>
<tr>
<td>Wood, Wood Products</td>
<td>Process Cooling &amp; Refrigeration</td>
<td>Electricity, Natural Gas</td>
<td>PJ</td>
</tr>
<tr>
<td>Primary Metals</td>
<td>Machine Drive</td>
<td>Electricity, Natural Gas, Distillate, LPG</td>
<td>PJ</td>
</tr>
<tr>
<td>Chemicals</td>
<td>HVAC</td>
<td>Electricity</td>
<td>CFM</td>
</tr>
<tr>
<td>Non-metallic Minerals</td>
<td>Lighting</td>
<td>Electricity</td>
<td>Lumens</td>
</tr>
<tr>
<td>Machinery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulp, Paper, Printing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport Equip</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Textile, Leather</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Rubber, Plastics</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Novel Research Questions –
Spatially Explicit H₂, Biomass, & CCS Infrastr. Develop.

- The goal is to incorporate our understanding about infrastructure. Significant experience with GIS/spatial and transition infrastructure models at UC Davis

- Complex infrastructure models to capture key issues:
  - Spatially explicit infrastructure models
    - Geography and distances
    - City sizes, clustering and demand density
    - Regional production and distribution solutions
  - Economies of scale of components
    - H₂ production and delivery
    - CO₂ transport and sequestration
  - Infrastructure evolution over a transition
    - Nature of infrastructure changes as function of size/scale

Thanks for your time.

Any questions?
Novel Methodological Contribution:
modeling optimal transition pathways under uncertainty

• Vast uncertainties in energy technology, energy demand, policy responses, …

• New model solution method: Progressive Hedging (PH) algorithm

• Under PH algorithm, TIMES is used to solve the scenario-based linear programming problem

• We expect to find the energy technology development strategies which account for uncertainties and the corresponding energy pathway
Motivation #1: Energy & Climate Policies

- AB32 (Global Warming Solutions Act)
  - Cap-and-trade
  - Low Carbon Fuel Standard (LCFS)
  - “Pavley” vehicle efficiency standards (AB 1493)
  - Early Actions (landfill CH$_4$ capture, High GWP consumer productions, heavy trucks, tire programs)
- Zero Emission Vehicle (ZEV) mandate
- Energy efficiency standards (appliances, buildings)
- Renewable Portfolio Standard for electricity (33% by 2020)
- SB375 (land use and housing)

California’s Global Warming Solutions Act (AB32):
1990 GHG levels by 2020; 80% reduction by 2050

Source: CARB (2009)
Motivation #2: Lack of Existing Models

- No comprehensive, long-term energy systems model for California exists.
- Current models:
  - e.g., E-DRAM and BEAR, Energy 2020, and E3 electricity models
  - Shorter timeframes (pre-2050); do not allow for the analysis of the full impacts of policies which call for drastic cuts in GHG emissions.
- CA policies need to be analyzed in a holistic framework.

Motivation #3: Build on Previous UCD Research

Meeting an 80% Reduction in Greenhouse Gas Emissions from California Transportation by 2050

![Graph showing greenhouse gas emissions](graph.png)

CA-TIMES model extends previous work

**Economics**
- Need to include costs and energy prices as decision variables
- In 80in50 studies, fuels and vehicle technologies are chosen exogenously. 80in50 model is scenario-based, not an optimization model.

**Dynamics**
- Transition pathway to 2050
  - Where do we need to be in 2020 or 2030?
- 80in50 study only provides snapshot of 2050

**Cross-sector Linkages**
- Varying marginal costs of abatement among sectors
  - 80% GHG reduction in transport sector may not be economically optimal
- Competition for limited primary energy resources (e.g., biomass)
- 80in50 study only focused on transport sector

Economic Models Supporting AB32 Analysis

**Energy 2020 (ICF)**
- Multi-region, multi-sector bottom-up simulation model: simulates changes in technology, energy demand, and prices as a result of regional cap-and-trade program.
- Not an optimization or cost minimization model

**E3 (SF-based firm)**
- Electricity and natural gas sector model

**E-DRAM and BEAR (UC Berkeley)**
- Computable general equilibrium (CGE) model ("top-down")
- Changes in gross state production, employment, personal incomes, and emissions

**MiniCAM (PNNL)**
- Provide CA Energy Commission capability to analyze electric and energy efficiency policies
- Top-down and bottom-up hybrid model linking climate, agriculture, energy supply, and demand systems.

*None have focused on the future drastic technological change in the transportation sector and the increasing interactions between the transport and the electric sectors.*
Major Advantages of the CA-TIMES Model vs. Other CA Energy-Economic Models

- We will produce a publicly accessible database, documentation, and model
  - Make the database and results publicly available and allow users to run alternative scenarios to understand potential carbon markets and optimize their own compliance strategies
- TIMES is a partial equilibrium model that integrates all sectors of the economy
  - Address investment, retirement, fuel switching, and retrofits decisions as well as system operation/optimization in dynamically integrated markets that may or may not be affected by AB32
  - Explicit infrastructure investment decisions
  - Estimate leakage
  - Capture rebound effects
  - Endogenous learning

Example Reference Energy System (RES)

Source: Uwe Remme, University of Stuttgart and IEA
TIMES Model Technical Details

- Technically speaking, the optimization problem in TIMES is not cost minimization, but rather the maximization of net total surplus (i.e., the sum of producers’ and consumers’ surpluses)
  - Total surplus is maximized at the point where the quantities and prices of the various commodities are in equilibrium, i.e. their prices and quantities in each time period are such that the suppliers produce exactly the quantities demanded by the consumers.
  - But...in truth, the maximization is performed as the minimization of “negative” surplus
- Equilibrium prices are equal to the marginal system values of the various commodities (whether an energy carrier, demand, material or emission)
  - Thus, one can call this “marginal value pricing”-- more appropriate than “marginal cost pricing”
- Assumes competitive markets for all commodities
- Departure from perfectly competitive market assumptions is possible by the introduction of user-defined explicit constraints, such as limits to technological penetration, constraints on emissions, exogenous oil price, etc. Market imperfections can also be introduced in the form of taxes, subsidies and hurdle rates.
- TIMES is a perfect foresight model (i.e., perfect information over the entire model planning horizon; each agent has complete knowledge of the market’s parameters, present and future)

Optimization problem

Decision variables (positive, continuous):
- Activity variables (Production level of technologies)
- Energy flows
- Investment decisions

Model constraints (linear constraints):
- Energy/ emission balances
- Efficiency relationships
- Utilization constraints
- Peaking eqn (reserve capacity)
- GHG mitigation targets, quota for renewables, ...

Objective function

\[
\text{Min } \sum_{i=1}^{n} c_i x_i
\]

\[
a_1 x_1 + a_{1,2} x_2 + \cdots + a_{1,n} x_n \geq b_1
\]

\[
a_2 x_1 + a_{2,2} x_2 + \cdots + a_{2,n} x_n \geq b_2
\]

\[\vdots\]

\[
a_n x_1 + a_{n,2} x_2 + \cdots + a_{n,n} x_n \geq b_n
\]

\[
a_m x_1 + a_{m,2} x_2 + \cdots + a_{m,n} x_n \geq b_m
\]

\[x_j \geq 0\]

- Standard TIMES model: Linear programming
- Implemented in modeling environment GAMS (General Algebraic Modeling System) for optimization/equilibrium problems
- Solution by interior point solvers (CPLEX, XPRESS)
- Variants of TIMES:
  i. Macro economic module -> Non-linear eqns -> Non-linear programming
  ii. Block-wise capacity expansion -> Binary variables -> Mixed-integer programming

Source: Uwe Remme, University of Stuttgart and IEA
Supply-Demand Equilibrium in TIMES

- Demand commodity is an **energy carrier** (or material or emiss. permit), whose production and consumption are endogenous to the model (e.g., gasoline)
- Demand function is implicitly constructed within TIMES, and is step-wise constant and decreasing for a single commodity

![Supp-Dem Diagram](image)

*Figure 3.1. Equilibrium in the case of an energy form: the model implicitly constructs both the supply and the demand curves*


Supply-Demand Equilibrium in TIMES

- Demand commodity is an **energy service** (e.g., LDV VMT)
- Demand function is defined exogenously by the user and then constructed in TIMES (user specifies an exogenous growth trajectory and a constant own-price elasticity for that demand)

![Supp-Dem Diagram](image)

*Figure 3.2. Equilibrium in the case of an energy service: the user, explicitly provides the demand curve, usually using a simple functional form*

Supply-Demand Equilibrium in TIMES

- Demand commodity is an **exogenously specified energy service** (e.g., LDV VMT)
- Demand (not demand function) is defined by the modeler (specify an exogenous growth trajectory, but no own-price elasticity for that demand)

![Equilibrium diagram](image_url)

**Figure 3.3. Equilibrium when an energy service demand is fixed**


**How supply-demand decisions are made**

![Supply-demand diagram](image_url)

**Typical representation of an energy commodity in MARKAL • TIMES. The algorithm maximises the global surplus over thousands such markets.**

TIMES Model Development and Status

**Primary Energy Supply**
- Renewables e.g. - Biomass - Hydro
- Mining e.g. - Crude oil - Natural gas - Coal
- Imports e.g. - Crude oil - Oil products
- Exports e.g. - Oil products - Coal
- Stock changes

**Conversion Technologies**
- Fuel processing: Plants e.g. - Oil refineries - Hydrogen production - Ethanol production
- Power plants e.g. - Conventional - Fossil Fueled Solar - Wind - Nuclear - CCCT - Fuel Cells - Combined Heat and Power

**End-Use Technologies**
- Industry e.g. - Steam boilers - Machinery
- Commercial e.g. - Air conditioners - Light bulbs
- Residential e.g. - Space heaters - Refrigerators
- Agriculture e.g. - Irrigation pumps
- Transport e.g. - Gasoline Car - Fuel Cell Bus

**Demand for Energy Service**
- Industry e.g. - Process steam - Motive power
- Commercial e.g. - Cooling - Lighting
- Residential e.g. - Space heat - Refrigeration
- Agriculture e.g. - Water supply
- Transport e.g. - Person-km

Endogenous Learning and Technological Change

Completed

Future work (near-term)

Future work (mid-term)