# MASTER

## DYNAMICS AND CONTROL:

**ENERGY CONVERSION, DELIVERY, AND DEMAND ANALYSIS**

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ABSTRACT

Techniques of mathematical modeling and modern control theory, using microprocessors and advanced measurement and control devices, are extensively applied to components and systems for the conversion and delivery of energy. The projection of energy demands, as a function of economic growth and energy price, is also the subject of active research and analysis. This position paper reviews the current state-of-the-art of analysis in these areas dealing with the planning and operation of energy systems that deliver fuels and electric power. Future research directions are also discussed.
INTRODUCTION

The operation of energy conversion and delivery systems of increasing complexity in accordance with high standards of safety, environmental control, and reliability poses significant challenges in the areas of mathematical analysis and control. New analytical techniques of mathematical modeling, stability theory, and control are being applied to individual components and processes as well as to the overall energy system. In addition to modeling and controls dealing with the operation of the physical systems that are employed to deliver fuels and electric power, analyses are also performed for such planning purposes as demand forecasting, investment strategy, and the planning of research and development programs.

In order to deal with the analytical methods that are employed for this broad and complex set of operational and planning issues, it is useful to consider the structure of the energy conversion, delivery, and utilization system. The structure of this system for the delivery and utilization of liquid and gaseous fuels, and electricity, is discussed in the next section in the context of The Reference Energy System (RES). The RES is a flow diagram representation of the energy system that has been applied to energy planning and analysis at the regional and national level in many countries.

Other sections of this review paper explore methods used for dynamic analysis and control at various levels of the energy system. The levels of application of dynamics and control analyses include the following.

1. Energy Conversion Applications: This category includes processes and systems used in the conversion of primary resources and refined fuels into forms suitable for delivery to consumers. Among the conversion processes and systems included in this applications area are combustion systems, fossil-fired electric plants, and nuclear-fueled plants. The analysis of dynamics and control at the plant level generally involves the coupled analysis of chemical/nuclear, thermal, hydraulic, and mechanical systems.
2. **Delivery System Applications:** This category includes systems employed for the delivery of secondary energy forms such as electricity, refined liquid products, gas, and solid fuels to consumers in residential, commercial, industry, and transportation sectors.

3. **Demand Analysis:** Energy is employed to produce a variety of services such as comfort, mobility, and employment. The type and form of energy needed, and the schedule on which it is required, is related to a complex mix of technical, environmental, economic, and social factors. This topical category includes the estimation of future energy demands in relation to these factors and to the relative price levels of alternative energy forms. There is extensive literature on dynamic analysis and control of energy utilization processes in the chemical and manufacturing industries, automotive propulsion systems, and the heating and cooling of buildings. These applications will be touched on, but a complete review of these specialized energy utilization topics is beyond the scope of this paper.

Applications of dynamics and control analysis that arise in the above three areas and that are reviewed in this paper include:

- dynamic behavior of components of system
- dynamic behavior of coupled systems and components
- stability of conversion and delivery systems
- scheduling of conversion systems
- optimal routing of secondary energy forms
- safety and reliability analysis
- measurement, estimation, and management of loads and demands
- investment decisions
- research and development planning

The specific analyses referred to in this paper are simply representative samples of the state-of-the-art; the compilation is not exhaustive and does not represent any comparative judgment of importance relative to other approaches.
THE ENERGY SYSTEM

The analysis of the complexities of the energy system to ensure reliable operation and adaptation to changes in demands and the resources that may be employed, requires a comprehensive perspective on the complete system. The overall energy system may be viewed as a technical system operating to apply energy resources to satisfy specific services to society. This technical system, governed by physical laws, operates in a complex economic and regulatory environment. This paper reviews the application of dynamic analysis and control theory to elements, processes, and subsystems of the energy conversion and delivery system. The relationship of energy demand to economic activity is also the subject of considerable analysis and is discussed from the perspective of integrated technical and economic analysis.

The Reference Energy System, Figure 1, illustrates the structure of the energy supply and utilization system. This description of the energy system provides a complete physical representation of the technologies, energy sources, through refining and various stages of conversion from one energy form to another, and through transportation, distribution, and storage of energy. In the Reference Energy System, energy supplies such as nuclear fuels, fossils fuels, and hydropower are allocated to energy demands defined on a functional basis, such as space heating, industrial process heat, and automotive transportation. The characteristics of utilizing technologies, which are important in identification of conservation and fuel substitution options, are included in this representation of the energy system at the same level of detail as supply technologies. The allocation of energy resources to specific demands depends on the energy technologies that are available for the production, transportation, distribution, and storage of energy and on the cost and efficiency of these technologies. In the Reference Energy System all energy flows are measured in British thermal units (Btu's).

In the Reference Energy System, energy supplies and demands are linked by energy conversion processes such as steam generation of electricity from coal. This particular process converts a primary energy supply, coal, into an intermediate form of energy, electricity. Electricity can then be used to satisfy
RESOURCE | REFINING AND CONVERSION | TRANSPORT | CONVERSION | TRANSMISSION AND DISTRIBUTION | UTILIZING DEVICE | END USE
---|---|---|---|---|---|---
NUCLEAR
2.0

GEOTHERMAL AND HYDROPOWER
3.1

COAL
14.0

(0.95)

(0.99)

(0.35)

NATURAL GAS
20.3

(0.65)

CRUDE OIL, DOMESTIC
19.6

15.0 IMPORTED OIL

TOTAL ENERGY, 1976
74.0

AVAILABLE ENERGY, 1976
63.9

54.9

27.5

48.6

13.5

FIGURE 1
Reference Energy System
demands for a variety of energy products such as base, intermediate, and peak-load electricity, space heat, air-conditioning, and water heat. For each process, the efficiency of conversion of primary energy supplies into intermediate forms of energy and the efficiency of conversion of the intermediate forms into final energy services or products can be specified. In addition, the cost and environmental characteristics of the technology or process may be represented for analytical purposes.

Of particular interest for the purpose of this paper are the portions of the energy systems dealing with the conversion and transmission/distribution of energy. In these categories of energy conversions and delivery, the topics discussed in the following sections include the following:

1. Conversion of fossil fuels and nuclear fuel to electricity
2. Transmission and delivery of electricity
3. Conversion of crude oil to refined liquid products
4. Transportation of solid, liquid, and gaseous fuels

The topic of demand analysis in relation to economic growth and other national policies is also addressed in this paper. A complete demand analysis requires consideration of the dynamics and control of a whole range of end use devices ranging from combustion burners through individual manufacturing processes to automobile engines and jet engines. Individual treatment of these end use topics is beyond the scope of this review; however, the overall topic of the relationship of energy demands (the right-hand side of the Reference Energy System) to economic development is discussed and methods of analysis are reviewed.
Applications of dynamic analysis and control to energy conversion processes range from individual processes such as combustion or chemical reacting systems to complete plants or facilities such as refineries, nuclear power plants, and fossil power plants. The use of more sophisticated control techniques in these conversion systems has been driven by a combination of factors including the need to meet environmental standards, increased reliability and safety, energy conservation, and cost reduction.

Dynamics analysis at this level is generally built on a physical model of the process or conversion and may involve several scientific and engineering disciplines, e.g., chemistry, physics, heat transfer and fluid flow, and mechanical structures. For systems operating under steady-state conditions or close to equilibrium, it is possible to develop a linear model defined around the steady state that is satisfactory for the analysis of small perturbations to the system. Under these circumstances the dynamics and control problem is a relatively simple one. In many instances; however, the primary interest is in the response to large perturbations where linear representations may not be valid or in processes operating at nonequilibrium conditions. Several coal liquefaction processes, such as flash hydropyrolysis, exploit non-equilibrium chemistry and fall into this latter category. In these instances, the problem becomes nonlinear and the advanced techniques of modern control theory and stability analysis must be applied. Often the complexity of the physical process is difficult to handle.

Combustion Process

The dynamic analysis and control of combustion processes seeks the objectives of high efficiency coupled with operational safety and control of such emissions as NO\textsubscript{x}, SO\textsubscript{x} and particulates. The parameters that may be monitored and controlled in the process include fuel flow, excess air, coolant flow and temperature, fuel-air ratio, flue gas composition, and flue gas temperature\textsuperscript{(2)}.
Mathematical models of the combustion process are needed for the design of new furnaces that offer significant improvements in efficiency and environmental characteristics. These are usually three-dimensional models that use finite difference or finite element techniques. Completely rigorous solutions for large commercial and utility furnaces are not available at this time.\(^{(3)}\) An example of the practical modeling of real furnaces is represented by Bueters,\(^{(4)}\) who developed a "slice model" in which the heat release (combustion zone) is defined in space along with further slices in space includes representation of the emissivity of CO\(_2\) and water vapor along with radiation and connection from post-combustion zones. Krishna\(^{(5)}\) has completed a review of furnace models covering stirred reactor models and fundamental models that use exact fluid mechanical equations. He concludes that major research needs related to the physical process include turbulence-kinetic interactions, spray effects for liquids and particle behavior in turbulent streams for solid fuels and kinetics. He also concludes that it is necessary to improve the numerical methods employed to obtain more rapid convergence and to deal more directly with boundary effects.

Combustion phenomena or of chemical reaction processes involve physical processes that are distributed in space and, thus, are described by partial differential equations. A rather complete review of the theory and application of control theory is contained in a series of lectures sponsored by the Naval Surface Weapons Center.\(^{(6)}\) A paper presented at that Conference by W. H. Ray outlines methods of state estimation and control of chemical reactors incorporating catalysts.

Crude Oil Refining

The techniques employed in crude oil refining emphasize optimization of conditions to achieve maximum yield of high value products. Techniques of mathematical programming have been applied rather extensively.\(^{(7)}\) These optimization models may use process descriptive coefficients obtained from physical models of individual steps or unit operations such as the combustion models discussed previously.
Fossil and Nuclear Electric Generation

The dynamic modeling of electric generating plants involves the coupled analysis of the heat generation process (combustion or fission), the steam cycle with turbine, and load interactions. The response of the plant and its control under conditions of load changes or in-plant changes are of particular interest. The sequence of processes and conversions, and the relevant parameters are listed below:

<table>
<thead>
<tr>
<th>Process or Step</th>
<th>Parameters of Interest</th>
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<tbody>
<tr>
<td>Heat Source—Nuclear</td>
<td>Fuel Temperature</td>
</tr>
<tr>
<td></td>
<td>Reactivity</td>
</tr>
<tr>
<td></td>
<td>Neutronics</td>
</tr>
<tr>
<td></td>
<td>Fuel Temperature</td>
</tr>
<tr>
<td></td>
<td>Core Reactivity</td>
</tr>
<tr>
<td>—Fossil</td>
<td>Firing Rate</td>
</tr>
<tr>
<td></td>
<td>Air-Fuel Ratio</td>
</tr>
<tr>
<td>Steam System</td>
<td>Pressure</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
</tr>
<tr>
<td></td>
<td>Flow Rate</td>
</tr>
<tr>
<td></td>
<td>Water Level</td>
</tr>
<tr>
<td></td>
<td>Steam Quality</td>
</tr>
<tr>
<td>Turbine &amp; Delivery System</td>
<td>Load</td>
</tr>
<tr>
<td></td>
<td>Synchronization With Grid</td>
</tr>
<tr>
<td></td>
<td>Speed</td>
</tr>
<tr>
<td></td>
<td>Process Conditions (P,T, etc.)</td>
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</table>

With regard to thermal powerplants, Debelle et al., in a review of applications and trends in automatic control for thermal power plant, (8) concludes that this is a very well developed field of automatic control. Problems encountered in start-up and shut-down, and in response to such system disturbances as generator outage, powerline trip-out, short circuits, frequency drop, etc. have stimulated considerable research. He states further that "automatic control of fossil-fired boilers is a problem which is considered as
having been solved for a number of years now when operated at rated capacity and when the perturbations affecting the process are of a small amplitude, i.e., not exceeding 10% of the maximum perturbation amplitude." Techniques of modern control theory are required for larger transients.

Recent interests in a wider range of plant operation and stability problems have stimulated work on applications of modern control theory, including optimization. Unfortunately, the criteria and parameters used in the optimization techniques do not always correspond with the physical characteristics of the components of the system. This problem apparently has led to a compromise which accepts a more simplified representation of the physical system to yield "quasi-optimal" solutions which are easier to implement in a real control system. It is clear that further research on the matching of more sophisticated plant optimization techniques with the physical processes and components is a fruitful field of research. Work along these lines is in progress in the electric generating field and should lead to other applications in the general area of energy conversion processes.

Debelle's review also deals with nuclear plant control and he states the view that "reactor control is essentially designed for reactor operations but that the requirements of the overall process, including turbine generator and network, are often neglected." Kerlin, in a comparison of model results with dynamic testing of three nuclear power plants finds that low order empirical models were capable of predicting plant behavior. These tests involved small power perturbations and essentially confirm the adequacy of existing models, even simple ones to handle small changes in conditions. The most comprehensive nuclear system model with the ability to handle large transients has been developed in the Reactor Safety Group at Los Alamos. This model deals with the coupled neutronics, thermal, hydraulic, and load response characteristics of the nuclear plant. It incorporates a three-dimensional representation of the two-phase fluid in the primary reactor vessel and has been used to estimate transient effects during a loss-of-coolant accident. The model at present does not provide for chemical reactions or the introduction of a third-phase such as the noncondensable gas generated in the Three Mile Island accident.
An increased role is foreseen for digital process computers in both fossil- and nuclear-fired plants. Most control functions are now served by conventional analog electronic devices having a few simple logic and control functions. This situation is changing very rapidly as more sophisticated hardware is being developed.
DELIVERY SYSTEM APPLICATIONS

Analyses of energy transport and distribution systems for solid fuels, liquids, gas, and electricity, generally lead to network problems with variable sources and demands.

In the case of transportation of solid, liquid, and gaseous fuels, analyses deal with the optimal scheduling and expansion of rail, pipeline, and tanker systems. These systems are characterized by high capacitance (storage capability); the dynamics of greatest interest are seasonally varying demands. A series of optimization models are employed to handle these problems. Of note are the Bechtel model for coal\(^{(11)}\), the Queen Mary College model of international oil trade\(^{(12)}\), and the Debanne model\(^{(13)}\) of pipeline networks for oil and gas. All of these involve mathematical programming, dynamic programming, or some variant of these optimization techniques.

Electrical networks pose a completely different set of problems requiring different techniques. The problems of network routing and expansion are fairly simple compared with the problems of stability under fault conditions, dynamic security, and the control of larger grids. Much of the research along these lines has been stimulated by blackouts and other failures that have had significant socio-economic impact. The network security problem involves contingency planning to determine the effect of outages and faults, and to determine means of solving these problems. The dynamic analysis deals with questions of stability of the system, in particular during transients associated with circuit faults. The transient and dynamic response problems in electrical networks have a fairly short time constant and typically are in the 0.1 to 5 hertz range. Techniques employed in stability analysis include the Lyapunov method, the method of hyperplanes in phase space, and transient energy methods\(^{(14)}\). The electrical system is also characterized by relatively low storage capability with major load variations on a daily, weekly, and seasonal cycle.
Considerable attention is being given to load management techniques in electric systems that automatically shed load selectively in response to ripple signals or other form of communication. (15) The obvious interest in some forms of load management as an alternative to the expansion of generating capability has led many to view the electric network as a communications system capable of sensing loads and controlling them.
DEMAND ANALYSIS

The state-of-the-art of energy demand analysis can be described in terms of four major steps in the sequence of energy conversions in the energy system starting with extraction of the primary resource.

1. extraction of energy resources
2. supply side conversion of resources into delivered fuels and electric power
3. end use conversion of delivered fuels and power into goods and services
4. consumption of goods and services in the economy

There are several energy resource models that describe the resource exploration, discovery, and extraction process. These include the gas model developed by MacAvoy and Pindyck and the coal model of Zimmerman among others. This step is not considered to be part of the energy utilization sequence so these techniques will not be discussed further.

The PIES model(16) employed in modified form by the Department of Energy for policy analysis includes a process description of the supply-side conversion of resources into fuels and power delivered to consumers. The system is being modified to include information on new energy technologies and has been used for energy supply and demand-projections to 1990. The model uses linear programming and has regional detail on both the resource supply-and fuel-demand side. The energy transportation infrastructure between regions is represented in the model.

In the PIES model, the demand for fuel and electric power is represented by a set of econometric relationships relating these demands to population, employment, GNP, and energy prices. Work is in progress to extend the process description into the energy utilization sectors so that specific end use technologies and policies may be represented. This work includes the Hirst model in the residential sector and several process models of energy in the steel, aluminum, paper, and petrochemical industries.
A comprehensive series of energy system and economic models employed at Brookhaven\textsuperscript{(17)} includes a process description of both energy supply and utilization. This process description is represented in network format by the Reference Energy System (RES), Figure 1. The level of detail on the end use side may be extended in the residential sector using the models developed by Hirst\textsuperscript{(18)} and Carhart.\textsuperscript{(19)} New technologies that are now in the R&D stage are represented in the RES and supporting simulation and optimization models. The Brookhaven Energy System Optimization Model (BESOM) is employed to analyze the optimal allocation of resources and selection of supply and end use technologies to satisfy a required level of energy services represented at the right-hand side of the Reference Energy System. The optimization may be performed with respect to a number of alternative objective functions including:

- total cost
- capital cost
- resource use
- imported fuel
- environmental effects

The energy system model has been employed in combination with the Hudson-Jorgenson model of the economy. The Hudson-Jorgenson model is used to represent the use of energy services of the economy and shows the effect of changes in the cost and availability of energy on the patterns of economic development. This combined model has been applied to long-term energy-economic projections over the period 1980-2000. The Brookhaven energy model has also been coupled with a fixed coefficient input-output model of the economy at the 110 sector level.

The structure of the energy utilization section of the Reference Energy System and the format of the Input-Output model that is coupled to it represent important departures from previous energy analysis work. Earlier work on energy systems analysis dealt with the supply of fuels and electric power and these same energy forms were defined as inputs to the economy in the input-
output matrix. Such a description of energy utilization provided little information on the characteristics of end use devices and of the use of energy services in the economy. This deficiency limited the understanding of the basic elements of energy conservation and of interfuel substitution.

The major advance represented in the Reference Energy System and the supporting energy models is the representation of end use devices and decentralized energy conversion devices at the same level of detail as supply technologies. This detail is essential to the analysis of conservation and fuel-switching policies involving research and development, efficiency standards, and/or taxes and subsidies.

The definition of energy products or energy services as inputs to the economy is also an important advance in improving both the process information that is available on the use of energy and the basis of econometric analysis of the demand for energy services. A coupled energy system—interindustry model has been developed in a single linear programming format by Dantzig.\(^{(20)}\) This procedure may be thought of as developing a rectangular input-output structure that can be solved as a linear program. The additional columns in the rectangular structure then represent alternative production processes that may be employed in the various sectors of the economy.

Several other energy models including the Decision Focus model\(^{(21)}\) and the Fossil I Energy Model\(^{(22)}\) use mathematical techniques other than mathematical programming but are consistent in structure and level of detail with the Reference Energy System format. These models incorporate more sophisticated simulation techniques for the dynamics of capital investment and the penetration of a new technology into the marketplace than are normally included in the optimization approaches. The simulation techniques employed in these models also use more of the traditional control theory approaches than the optimization techniques. Current research activities are directed towards the structuring of the optimization models in an optimal control theory format. Kydes\(^{(23)}\) has developed a time-step or forward difference equation representation of an optimization model that opens this class of models up to improved
simulation capability through the improved representation of investment decisions and market penetration. This time-step optimization approach, where a new optimization is performed for each time-period on incremental additions to capacity and replacements, is to be contrasted to the usual time-phased optimization models where all time periods are included in a single linear programming with assumed perfect foresight over the long term on future events. Dantzig and Perold\(^{(24)}\) have extended their work on decomposition techniques for solving the staircase structure of the large time-phased models to the formulation of such models in the form of difference equations with a basis in control theory.

The problem of market penetration in large energy system models has been mentioned and arises in any long-term energy model that includes a representation of new energy technologies. The most recent advance on this problem has been made by Peterka\(^{(25)}\) at the International Institute for Applied Systems Analysis. He uses a logistic substitution curve to arrive at market shares for competing technologies and tests the model using historical data from several countries.

The energy system economic models described above have been used in a variety of energy policy studies that emphasize the high national importance of energy conservation and fuel substitution. Such analyses require the detailed treatment of energy use and stress the relationship between energy use and economic growth. In addition, the effect of taxes, regulation and other Federal policies on energy use are evaluated with these models.

The applications of dynamic analysis and control to specific processes, devices, and systems which use energy in buildings, industry, and transportation are numerous. The proceedings of the 7th Triennial World Congress of the International Federation of Automatic Control (IFAC) included special session on control applications to integrated steel plants, pulp and paper plants, chemical processes, automotive engines, and buildings, mostly for purposes of improved energy conservations.
CONCLUSIONS

The research needs in the dynamic analysis and control of energy conversion, delivery, and utilization processes involve several general areas. These include research on mathematical techniques, research to improve the understanding and characterization of the physical system being modeled, and research on control devices. With respect to control devices, the areas of measurement, control logic, information processing, and control functions are of special importance.

At the process level, including both conversion and delivery systems, the primary research problem must be viewed as improved characterization or description of the physical system being analyzed. Even with progress on this front, however, control theory must continue to deal with an inadequate physical description of the process, poor information on the state of the system, and a simplified control objective. Progress will come through the use of microprocessors that can deal with more complex logic functions and improved physical understanding of the system being controlled. Of special interest are stochastic analysis and adaptive control methods. In view of the role of human operations in control systems, particularly when emergency intervention is required, increased attention must be given to the control system human interface.

In the analysis of energy conversion, delivery, and demand, current research is being directed to the coupling of analytical techniques appropriate to individual portions of the energy system. Coupled differential equations, sometimes nonlinear, are employed to describe the dynamics of energy conversion processes such as combustion and chemically reacting systems, and of electrical networks. Optimization techniques are employed for analysis of scheduling and capacity expansion of conversions and delivery systems; while econometric techniques are used for demand analysis.
The usual approach to coupling such disparate techniques is to run them sequentially with key information exchanged manually between models. This iterative approach raises questions of convergence, uniqueness, and stability of solutions that must receive increased research attention. Efficient solution methods are also needed which still allow participation by the analyst in interpreting information flowing between modules or models.

There is a creative tension in existence between the methods of control theory analysis, such as systems dynamics, and classical demand analysis techniques, such as econometrics. In the former case, it is clear that systems dynamics has a rich structure including feedback and nonlinear relationships that facilitate an improved physical description of the system including an explicit representation of causal relationships. The drawback is that the technique does not admit to a clear indication of sensitivity and propagation of errors.

Econometrics, on the other hand, is well developed for sensitivity analysis and propagation of errors through coupled systems of equations. This technique, however, does not admit the complex causal relationship that can often be identified in physical systems.

Recent research on multilevel hierarchical controls and decentralized controls appears to have application to economic systems and energy demand analysis. The modeling of large-scale integrated manufacturing facilities illustrates difficulties that arise in the measurement, logic, and control of production systems even when a complete physical description is, in theory, possible. The modeling of socio-economic systems is clearly much more difficult but the methods of decentralized control can provide significant insight into the effect of quality of information and decision processes on the system.
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