Modeling Energy System Information Flows

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***Abstract*—Motivated by an interest in multi-agent systems and by the need to improve coordination within competitive energy systems, this work addresses techniques to model energy system information flows. We take a broad view of the energy system as including the electric, gas, coal, and water systems, noting the symmetry associated with the fact that each of these subsystems depends on the integrated operation of a network together with a market, and noting the strong coupling within and between the different energy subsystems. This coupling largely occurs through information flows between different decision-makers and between the decision-makers and the information repositories. Specifically, this paper is concerned with a method to model these flows in order to identify ways to provide that the information, on which the decision-making is based, be more efficiently processed and obtained.**

***Keywords*—Causal loop diagrams, energy system, information flows, multi-agent systems, stock and flow maps, system dynamics.**

I. INTRODUCTION

IN this paper, we use the term energy system to refer to the integrated infrastructure associated with the production, transportation, storage (where applicable), and end-use of four different energy forms: electricity, gas, coal, and water, each of which we refer to as a subsystem of the energy system. The four subsystems, although clearly having their own unique characteristics, also share important common attributes, among which are that each subsystem utilizes networks and financial markets for transporting and trading, respectively, its energy form. The energy system is, therefore, a new type of system that is uniquely large and uniquely constituted, requiring, on the one hand, coordinated decision-making in order to maintain reliability of highly technologically advanced and fragile interconnected and interdependent systems, and on the other, decentralized and autonomous decision-making in order to maintain a competitive market.

Low price and high reliability are society's twin energy-related objectives. The extent to which they are achieved is a major influence on the economic national health. As a result of the recent industry restructuring, it is no longer the case that energy price and reliability are determined by a centralized organization, the utility, overseen by a regulatory body. Rather, we observe that today, energy price and reliability are determined by the aggregation of certain types of decisions made over multiple time frames by a multiplicity of highly distributed decision-makers using information from many different sources. Although the industry has attempted to place some structure on some decisions, it has not yet solved the fundamental problem presented by the need to facilitate coordinated decision-making between competing decision-makers. We desire to address this challenging problem, motivated by its intellectual difficulty, its applicability and significance to various fields.

Autonomous agents and multi-agent technology is one of the landmark events in the computer science community of the '90s. Agents are bringing together ideas from many disciplines: artificial intelligence, distributed processing, sociology, organizational and management science, but also biology, psychology, and philosophy. Multi-agent systems (MAS) may be viewed as a collection of distributed autonomous artifacts capable of accomplishing complex tasks through interaction, coordination, collective intelligence, and emergence of patterns of behavior [1], [2].

In previous work the multi-agent approach was used to develop a prototype that enables software representation of human decision-makers for electric power systems, using inter-agent communication, coordination, and negotiation capabilities [3]-[5]. Our experience with this prototype system suggests it has significant potential for facilitating the complex decision-making problems inherent to competitive energy systems, because of its ability to operate efficiently in networks interconnecting distributed decision-makers and information repositories (e.g., distributed computing can be accomplished with no additional network programming), and because of the flexibility associated with the design of individual software agents. Key to effective MAS implementation is identification of decision, decision-makers, and relevant information. The effort described in this paper begins this identification. In doing so, we aim to model information flow.

This model will consist of decision and information nodes together with interconnects representing communication mediums between the decision-makers and the information used to make the decisions. The model will be used to identify potential new and more efficient information flow paths that may result from elimination, bypassing, or aggregation of some decision centers or information repositories. Furthermore, we also aim to draw conclusions regarding the performance of different levels of decentralized decision-making vs. centralized decision-making. We believe that these conclusions will enable us to identify enhancements to the energy system information network.

In section II we illustrate the interactions among the functionalities of the energy system by describing the coupling within the energy subsystems and between them. The decision-making process is addressed in section III. Basic tools of systems dynamics modeling are introduced in section IV. Finally, section V summarizes the work and refers to the future research directions.

II. COUPLING WITHIN AND BETWEEN ENERGY SUBSYSTEMS

We focus on the primary non-transportation energy sources as comprising what we define as *energy system*. This includes the subsystems of electricity, natural gas, coal, and water. The last three subsystems, gas, coal, and water, are interlinked through the first form, electricity, with the energy supply to electricity being comprised of about 14.8% natural gas, 52.3% coal, and 6.2% water, with the remainder being mainly nuclear (22.0%), petroleum (2.2%) and other various alternative forms (2.5%) such as biomass, geothermal, wind and solar [6]. Of these, the gas, coal, and water subsystems share a common characteristic with electricity in that their respective transportation systems can be viewed as a network consisting of nodes and branches. Electricity, with its transmission system interlinking the generators and load centers, and gas, with its pipeline system interlinking the wells, storage facilities, and load centers, are well known as networked systems, both are controlled by centralized system operators, and both are subject to disruptions having potential to incur significant cost-consequence. The transportation systems associated with coal, mainly rail and navigable rivers, may also be viewed as networks. Similar to electricity and gas networks, rail and river navigation are controlled by centralized system operators, and both, particularly rail, are subject to disruption. Finally, river/reservoir systems from which we derive most of our hydroelectric energy, and which is generally distinct from the navigable river systems, may also be viewed as a network.

Electricity, gas, and coal share a second common characteristic: there exist financial markets for all three in which the energy form is traded as a commodity. These financial markets may be classified as spot or cash markets and futures markets. Spot markets exist for electricity (PJM, Cal-ISO, NY-ISO, ISO-New England, Into-Cinergy, MAPP, ComEd), for natural gas (Henry hub, New York citygates, Chicago citygates, Northern and Southern California), and for coal (Big Sandy shipping terminal, Huntington Beach). Futures markets exist for electricity, gas, and coal at the New York Mercantile Exchange (NYMEX), the Chicago Board of Trade (CBOT), and the Chicago Mercantile Exchange. For example, NYMEX offers futures contracts for electricity at Cinergy, the California-Oregon boarder, Palo Verde, PJM, and Entergy, for gas at Henry Hub, and for coal at Central Appalachian. Water also has a presence on the NYMEX futures markets via Mid Columbia River electricity contracts.

Each energy subsystem (electricity, gas, coal, and water) may be described in terms of the coupling within them and the coupling between them. The intra-subsystem coupling exists between four basic functionalities: supply, transportation (the networks), storage (except for electricity), and demand. These couplings are illustrated in the influence diagram of Fig. 1, using the light lines. For example, the arrows from the natural gas demand to its supply and transport functions indicate that the demand of natural gas influences its supply and transport, an obvious intra-system coupling that is apparent for electricity and coal as well. The supply for water, on the other hand, is independent of its demand, but rather determined by rainfall and snow runoff. The arrows from the natural gas supply and transport to the demand function indicate that limited supply and transport can in turn influence demand, as demand can be curtailed if the supply or transport capability is insufficient. This feature is also seen in the electricity and coal subsystems. Inter-subsystem coupling is illustrated in Figure 1 using the heavy lines. The fact that most of the heavy lines connect to the electricity subsystem indicates that it is mainly through it that the four subsystems interact. For example, the supply of electricity largely determines the demand for coal and natural gas. Likewise, if the demand for coal or natural gas is limited, then this limitation may also limit the electricity supply. Electricity supply also affects, and is affected by, water storage in reservoirs and the associated scheduling of reservoir-hydroelectric units. Run-of-the-river hydroelectric units, on the other hand, are normally not scheduled per se but rather run to capacity; as such, they are considered as directly decreasing the electricity demand. Although most rivers used for hydroelectric generation are not used for coal transport, there are some exceptions, and thus there may be some coupling between river and coal transport. One unique inter-subsystem coupling occurs between gas and electricity demand. The reason for this is that many customers have capability to use either gas or electric heat.

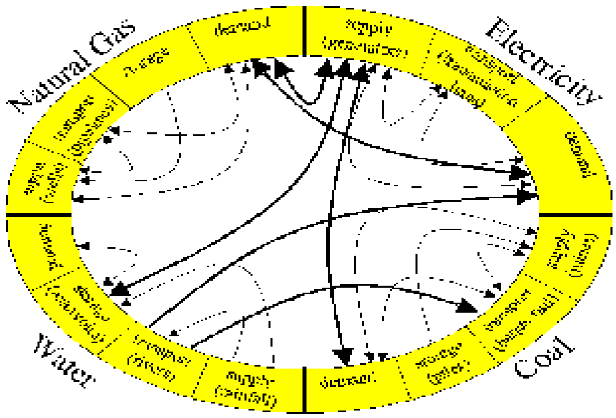

Figure 1 – Intra-subsystem coupling (light lines) and inter-subsystem coupling (heavy lines)

All energy systems are vulnerable to disruptions. These vulnerabilities can be found in the supply, transportation, storage, or demand functions of any of the subsystems, and they may be divided into four rough categories:

- Natural causes (temperature extremes, heavy precipitation, drought, earthquakes, storms, and ice);
- Primary equipment failure due to accidents or wear out (circuit faults, generator forced outages, pipeline ruptures, and railway disruptions);
- Labor unavailability, particularly with unionized rail or coal mine workers;
- Failures in information transfer via communication mediums.

Occurrence of one or more of these disruptions causes undesirable effects to propagate through the energy system, usually resulting in pronounced observability of the various intra- and inter-subsystem couplings that were described above. Usually, this observability occurs through the price and availability of an energy source or its transportation function, both of which are observable in the spot and futures markets.

Energy systems are saturated with decisions and information, and both are highly distributed. We also note that decision-makers make decisions based on the information that they have. The decision-makers can effectively use information to make good decisions when they can: (1) identify the value that is relevant to the decision, (2) know where the relevant information is located, (3) gain access to it, (4) move and process it (or process and move it), and (5) integrate and synthesize it. We are motivated to enhance each of these attributes of information flow. We base our work on the following underlying two-part thesis: (a) There exist energy systems information networks through which information flows. We can identify these networks and associated flows, model them, study them, and identify their characteristics, requirements, and influence, and we can control and optimize them. (b) Energy system reliability and economic efficiency is driven by energy subsystem intra- and inter-subsystem coupling; this coupling occurs through information flows. From (a) and (b), we conclude that controlling and optimizing information flows is key to energy system reliability and economic efficiency.

Figure 2 illustrates our approach to the study of energy system information flow in terms of the steps we are taking and the ultimate goal that we have. Although our work in developing taxonomies and models is still early, we provide some discussion of these areas in the remainder of this paper. We do not further address MAS within this paper, but references [3]-[5] describe our direction in regards to it.

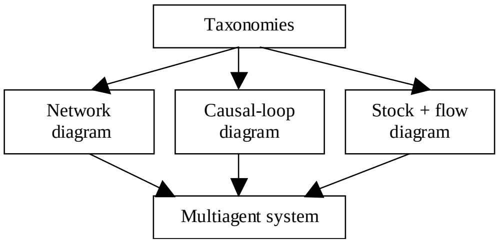

Figure 2 – Energy System Information Flow Study Approach

III. DECISION TAXONOMIES

As stated before, the couplings among the different functionalities of the energy subsystems revolve around price and availability of an energy source or the price and availability of its transportation function. These two attributes, price and availability, are determined by the aggregation of certain types of decisions made by energy system participants. There are two basic characteristics of energy systems that make this decision-making process complex. One concerns the decision-makers and their decisions, and the other concerns the information and corresponding information flow paths utilized by the decision-makers. We offer taxonomies for each in what follows.

A. *Decision-makers*

There are a large number of decision-makers situated in many different organizations, each of which have unique objectives, and many of which are competing for the same resources. These decision-makers may be roughly classified into two main groups: market players and overseers. The market players are comprised of energy sellers, energy buyers, and network owners. The overseers are comprised of network operators, network regulators, and energy market regulators.

B. *Decisions*

The decisions themselves are characterized by the objective and corresponding alternatives, the amount of time between "now" and actuation of subsequent actions, referred to as the decision horizon, and the information requirements associated with the decision. Furthermore, these decisions have multiple decision horizons; these may be classified as near-term (0-24 hours), mid-term (1 day to 1 year), and long-term (1-10 years and beyond). A rough classification of these decisions, by objective, is supply, transport, delivery, and demand, and for each, the alternatives are segregated by price, quantity, and facilities. Table 1 summarizes the decision-makers and illustrates the various decisions in which each is involved for near-term decision-making. In this table, “ √ ” indicates the decision-maker is involved in the decision, “blank” that the decision-maker is not, and “O” that the decision-maker is an information supplier but does not participate in the decision. Similar tables can be developed for mid-term and long-term decisions.

Table 1 – Near-term decisions and decision-makers

Function	Decisions	Decision-Makers					
		Market Players			Overseers		
		Energy seller	Network owner	Energy buyer	Network operator	Network regulator	Energy market regulator
Supply	Quantity	Ö		Ö			**O**
	Price	Ö		Ö			**O**
	Facilities	Ö		Ö		**O**	
Transport	Quantity	Ö	Ö	Ö	Ö	**O**	
	Price	Ö	Ö	Ö		**O**	
	Facilities	**O**	Ö	**O**	Ö	**O**	
Delivery	Quantity	Ö		Ö	Ö		**O**
	Price	Ö		Ö			**O**
	Facilities	Ö	**O**	Ö	Ö	**O**	
Demand	Quantity	Ö		Ö			**O**
	Price	Ö		Ö			**O**

C. *Information*

Table 2 summarizes the information that is used in decision-making pertaining mainly to the electricity subsystem. Different types of information are identified, organized by function, nature (which corresponds directly to the decision), and the timeframe characterized by the information. Similar tables can be developed which indicates the physical location, accessibility, and processing requirements of this information. These information repositories include databases located in the intelligent electronic devices of substations, network regulators and scheduling coordinators (e.g., transmission system capacities and service pricing are given in the OASIS), energy management systems, spot and futures market systems, transmission companies, distribution/delivery companies, customers, and weather forecast providers.

D. *Information Flow Paths and Network Diagrams*

A decision-maker obtains information from the repositories, and we say that this movement occurs over an information flow path. Information flow paths are characterized by the communication medium (e.g., web, e-mail, telephone, LAN, virtual private network), its availability, latency, and bandwidth, and the decision-maker/repositories linked. We may therefore model the decision-makers/repositories as nodes and the flow paths as branches within a network diagram. A computer model of the network diagram can take advantage of many standard network analysis methods, e.g., node-incidence matrices. Key to this effort is clear characterization of information quantification and branch capacity.

Table 2 - Information associated with electricity subsystem decision-making

	Nature of Info	**Timeframe**		
		History (past)	**Real-time (present)**	**Predictive (future)**
Supply	Quantity-related	Demand, supply, fuel histories	Demand, supply, fuel	Weather, demand, fuel forecast
	Price-related	Fuel, wholesale energy spot price histories	Fuel, wholesale energy spot price	Fuel, elect. Energy futures price
	Facilities-related	Gen operation histories, gen equip. integrity monitoring data	Generation capacity, emissions, ST gen equipment integrity, demand, UC, ancillary services	LT gen equip. integrity, maintenance schedules, outage impact, new facilities
Transport	Quantity-related	MW flow, ATC histories	MW flow, ATC	Weather, demand, supply forecast
	Price-related	Transmission service cost	Transmission service price	Future transmission service price
	Facilities-related	Trans. operating histories, trans. equip. integrity monitoring data, disturbance records	Operating conditions, limits & security levels, ST trans. equipment integrity	LT trans. equip. integrity, maintenance schedules, outage impact, new facilities
Delivery	Quantity-related	Demand, supply histories	Demand, supply, demand control + interruptibility	Weather, demand, supply forecast
	Price-related	Wholesale, retail energy spot price histories, delivery service cost	Wholesale, retail energy spot price	Electricity energy futures price, forecast retail spot price
	Facilities-related	Operating histories, delivery equip. integrity monitoring data	Delivery capacity, ST delivery equipment integrity, PQ, demand	LT delivery equip. integrity, maintenance schedules, outage impact, new facilities
Consume	Quantity-related	Demand, delivery histories	Demand control + interruptibility	Forecast electricity energy needs
	Price-related	Retail energy spot price histories	Retail energy spot price	Forecast retail spot price
	Facilities-related	End-use equip. integrity monitoring data	End-use equipment operability	Back up supply

IV. MODELING THE SYSTEM DYNAMICS

To facilitate study of the energy system, we appeal to the discipline of system dynamics [7], as it has been well articulated and proven, it offers a systematic method appropriate to the objective, and it is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics, and engineering. System dynamics comprises a variety of diagramming tools to map the system structure. These include causal loop diagrams and stock and flow maps. They are both qualitative modeling techniques that can easily be translated into simple mathematical expressions needed to quantitatively validate the conceptual framework. Whereas the network diagram models information itself, the causal loop diagram and the stock and flow map model commodities – in our case – energy. We expect that these commodity-modeling techniques will illuminate a great deal regarding information flow. In addition, we are interested to discern whether we may treat information as a commodity itself and use these commodity-modeling techniques directly.

A. *Causal loop diagrams*

Causal loop diagrams are flexible and useful tools to represent the feedback structure of a system. Causal diagrams are simply maps showing the causal links among variables with arrows from a cause to an effect [7], [8]. Figure 3 shows an example concerning the electricity used for heat.

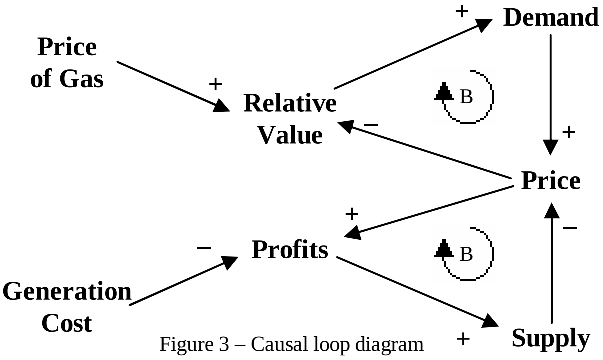

Figure 3 – Causal loop diagram

This method of model construction evolves by identifying loops and linking them together. The variables are related by causal links, shown by arrows. In the example, the variable *profits* is determined by both the price and the cost of production. Each causal link is assigned a polarity, either positive (+) or negative (–) to indicate how the dependent variable changes when the independent variable changes, assuming all other variables are constant. A positive link means that if the cause increases (decreases), the effect increases (decreases) above (below) what it would otherwise have been. On the other hand, a negative link means that if the cause increase (decreases), the effect decreases (increases) below (above) what it would otherwise have been. Mathematically, a positive and a negative link polarity are represented by a positive and a negative first order derivative, respectively.

The important loops are highlighted by a loop identifier, which shows whether the loop is a positive or negative feedback. Positive feedback loops are also called reinforcing loops and are denoted by a **+** or **R**, while negative feedback loops are also called balancing loops and are denoted by a **–** or **B**. Sometimes specific names are also given to the loops to make it easier to read and understand the diagrams.

In the example illustrated in Figure 3, the electricity demand for heat purposes responds to its relative value compared to the substitute (in this case, gas). Higher relative value increases demand, bidding prices up and lowering relative value. Supply expands when profits rise, and profit depends on price relative to production costs. Greater supply drives the price down, lowering profits. Mathematically, we can model these relationships using derivatives, such as:

$$\frac{\partial\, Price}{\partial\, Demand} > 0 \qquad \frac{\partial\, Price}{\partial\, Supply} < 0$$

It is interesting to note here that the polarities assigned to the links describe the structure of the system, but they do not describe the behavior of the variables. That is, they express what would happen *if* there were a change. They do not explain what actually happens in terms of which direction the variables do change.

Both loops shown in this example represent balancing feedbacks. In fact, if a there is a small disturbance in one of the variables in the loops, it will propagate around the loop to oppose the original change. In the demand loop shown in Figure 3, let us assume that the relative value of electricity increases. Because the link from relative value to demand is positive, the demand increases. Because the link from demand to price is again positive, price rises. But because the link from prices to relative value is negative, as the price rises there is depreciation on the relative value of electricity. Therefore, the feedback effect opposes the original change, so the loop is negative, representing a balancing or self-correcting effect. Mathematically, the loop polarity corresponds to the sign of the open loop gain of the loop. Let us consider again the demand loop in our example. To calculate the open loop gain we must choose a variable (for instance, demand) and break the loops there, splitting the chosen variable into an input and an output (demand^i and demand^o, respectively). The open loop gain is defined as the partial derivative of the output with respect to the input, that is, the feedback effect of a small change in the variable as it returns to itself. The polarity of the loop is then the sign of the open loop gain:

$$Polarity\ of\ loop = SGN\left(\frac{\partial demand^{o}}{\partial demand^{i}}\right) =$$

$$= SGN\left[\left(\frac{\partial demand^{o}}{\partial relative\, value}\right)\left(\frac{\partial relative\, value}{\partial price}\right)\left(\frac{\partial price}{\partial demand^{i}}\right)\right]$$

Since the product of two negative signs is a positive sign, negative loop polarity requires an odd number of negative links in the loop. So, a fast and easy method to determine if a loop is positive or negative is to count the number of negative links in the loop. If the number of negative links is even, the loop is positive; if the number is odd, the loop is negative.

Positive feedback loops generate growth, amplify deviations, and reinforce change. Negative loops seek balance, equilibrium, and stasis. Two fundamental modes of dynamic behavior, the exponential growth and the goal seeking, arise from positive and negative feedback, respectively. In the presence of an exponential growth behavior, the larger the quantity, the greater its net increase, further augmenting the quantity and leading to ever-fast growth. On the other hand, when goal seeking characterizes the behavior of the system, the negative feedback loops act to bring the state of the system in line with a goal or desired state. The state of the system is compared to its goal, and corrective actions are taken to eliminate any discrepancies.

Another important structure that sometimes is useful to show explicitly in a causal loop diagram is a delay. Delays are one of the major factors contributing to system behavior over time. They give systems inertia, can create oscillations, and are often responsible for trade-offs between the short-and the long-term effects of decisions. In the example shown in Figure 3, when the supply rises, the price tends to decrease, and when the demand increases, the price will likely increase. However, these reactions may not be perceived until after significant time delays. As we will see in the following, delays always involve stock and flow structures.

Two fundamental behaviors of dynamic systems were mentioned before: the exponential grow and the goal seeking. The former is modeled through a positive (self-reinforced) feedback, while the later is represented by a negative (balancing) feedback. Another fundamental behavior observed in dynamic systems is oscillation. Like goal seeking, oscillations are caused by negative feedback loops. The difference is that oscillations occur when there are delays in at least one of the links in the negative loop.

B. *Stock and flow maps*

While causal loop diagrams emphasize the feedback structure of a system, stock and flow diagrams refers to their fundamental physical structure [7], [8]. Stock and flows track accumulations of material, money, and information as they move through a system. Stocks are elements in the system that can potentially accumulate or decline. They include inventories of product and financial accounts. Flows are the rates of increase or decrease in stocks, such as production and shipments. Stocks characterize the state of the system and generate the information upon which decisions and actions are based. The decisions then alter the rates of flow, altering the stocks and closing the feedback loops in the system [9].

In the notation of the stock and flow diagram, stocks are represented by rectangles, flows are represented by arrows, valves control the flows, and clouds represent the sources and sink for the flows. A simple example of a stock and flow diagram is presented in Figure 4. In this case, production is the inflow, while shipments is the outflow. The variable inventory is the stock. Stocks are known as integrals or state variables and flows are known as rates or derivatives.

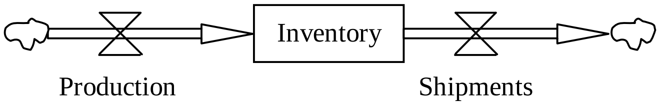

Figure 4 – Stock and flow diagram

Mathematically, the model can be reduced to a set of equations, where the accumulations (stocks) are represented by the integral of their flows according to the following expression:

$$Stock(t) = \int_{t_0}^{t} \left[Inflow(s) - Outflow(s) \right] ds + Stock(t_0)$$

In the causal loop diagrams there is no distinction between stocks (the accumulations of resources in a system) and flows (the rates of change that alter those resources). In the example illustrated in Figure 3, the price variable is indeed a stock, while demand and supply are flows.

As mentioned before, delays in the system are related to the stock and flow structures. A delay is a process whose output lags behind its input. The difference between the input and output accumulates in a stock of material in process. In the case of gas transportation, for instance, there is a delay between the time the material enters the pipeline and the time it is received at the exit end. The gas in transit inside the pipeline is the variable that represents the accumulation, i.e. the stock, while the inflow rate and the outflow rate are the variables that correspond to the flows. Neglecting the mixing between different shipments and the individual transportation times, causing some variance in the distribution of the deliveries, one can say that the outflow is simply the inflow lagged by the average delay time D:

$$Outflow(t) = Inflow(t - D)$$

When there are important delays to be modeled, it is easier to include the stock and flow structure in a causal loop diagram to represent them. With the causal loop diagram representation it is hard to identify the physical flow of a product through the system and the accumulations in the stock and flow chain. In general, a mapping system structure consists of networks of stock and flows linked by information feedbacks from the stocks to the rates, i.e. the flows.

A system dynamic model represents a decision-making structure [10]. In this context, decision-makers are viewed as information converters to whom information flows and from whom come decisions that control actions within the complete system. The energy system is a complex multiple loop and interconnected system. The decisions made at multiple points will generate information that may be used at several, but not necessary at all, decisions points. Decision-making is therefore a continuous process, a conversion mechanism for changing flows of information into control signals that determine the rates of flow in a system.

V. CONCLUSIONS

This paper addresses the energy system as a complex dynamic system involving the main functionalities of four energy subsystems (electricity, gas, coal, and water) and the coupling among them. Some of the modeling tools used to study the system dynamics are discussed.

Network models effectively show the information flow paths between data repositories and decision-makers, but quantitative characterization of corresponding network elements must be accomplished. Causal loop diagrams are a very useful tool to represent interdependencies and feedback. However, they suffer from some limitations, such as their inability to distinguish between the stock variables and the flow variables. Stocks and flows, along with the feedback structure of the causal loop diagrams, are the two central concepts of dynamic systems theory. The authors believe that these techniques will help developing a model to learn about the energy system, which will enable the identification of enhancements to its information network.

The achievement of a good balance between (a) the required coordination of the physical operations of energy systems, necessary for maintaining the reliability of the network, and (b) competition between participants, particularly the suppliers, is the ultimate objective of the complete procedure. The broader impacts to accrue to the society and to the economy at large are due to improved information flow and decisions in the vital energy sector.

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VII. BIOGRAPHIES

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