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Feedback Control Model of Regional Energy Systems

1. ABSTRACT

The only way to achieve a sustainable society is to have a sustainable energy system, where the daily activities of individuals and businesses are carried out within environmental constraints. The critical and necessary first step for achieving a sustainable society is to discover what a sustainable society is. This paper presents the idea that the concept of sustainable society can be understood through control system theory. An original energy system model for a generic anthropogenic activity system is described. The model is shown to predict the "tragedy of the commons" when certain feedback and control elements are not present. The model implies that sustainability engineering must start with conceptualization of a hypothetical sustainable system, and must address the information and communication technology required for continuous environmental resource monitoring. Only after this reference system is understood and feedback technologies are invented, can sustainable development decisions in the present system be effectively pursued.

Key words: sustainability, systems analysis, engineering economic theory, strategic policy

2. INTRODUCTION

Most people recognise that using fossil fuels and finite resources supports the present economy, activity systems and living standards. Most people also recognize that present energy consumption rates and environmental impacts are not sustainable. Engineers are seldom involved in political, business or government decisions about energy and economic policy or long-range strategy. Economics is currently perceived to be the driver for behaviour and decision making, while engineering provides the goods and services demanded by the market. The law of supply and demand is widely understood and is believed to be relevant to the economy while engineering fundamentals are not. The public looks to science and technology to fix problems like pollution, and to develop new technologies to provide more energy to sustain consumption growth. People look to the economy to sustain their lifestyles, and to politicians to sustain the economy. Indeed, the human project has always been a complex system of individual perspectives, activities and motivations. Differentiation and specialization is understood to underpin the progress of civilization, but this paper presents a view that integration and systems-level interconnections are key elements of anthropogenic continuity. Indeed, it is proposed that systems-level dynamics is the key to sustainability rather than individual technology or infrastructure components.

2.1 Disciplines and Directions

Economics studies how people choose to spend their available money to maximize and continually increase their utility, the satisfaction they derive from consumption. Science is defined as the continuous process of observing, modelling, testing and predicting phenomena. Engineering is the art of applying science to generate assets using available natural resources in order to provide services and products for trade and to support wellbeing. As a general observation, engineers have historically been successful at designing and building the infrastructure, manufacturing the products and producing the energy that provides society's standard of living through a wide range of economic arrangements. The vast majority of this engineering work is done on a project-by-project basis, with project objectives set to take advantage of opportunities, build capacity, provide services or mitigate problems. Systems-engineering has developed because of highly complex, multidisciplinary and constrained engineering projects like aeroplanes, handheld electronics, robotics and weapons systems (Kossiakoff & Sweet 2002). This engineering discipline develops whole complex systems by concurrently addressing component technologies, integration capabilities, and fundamental sciences in the context of the constraints on the whole system (Wasson 2005). For example, during the development of a new aircraft concept, a large and diverse cohort of engineers, scientists and modellers work in different ways, but toward a common concept and within the aircraft's weight and dimensional constraints to suit a specific market.

This paper examines the proposition that economics, engineering and science cannot independently fix the serious energy supply and environmental problems now facing us by focusing on component-level projects such as extracting more renewable energy, improving efficiency or changing consumer behaviour. Nor can we transition toward sustainability as long as the context for decision-making is primarily continuous growth of the economy of consumption. The evolution to sustainability cannot be achieved simply by incorporating the cost of environmental impacts into the cost of products and services. There must be some new, systems-level, multidisciplinary approach to sustainability.

2.2 Thesis: Sustainability Requires New Practices in Engineering and Economics

A multidisciplinary group of researchers and students at the Advanced Energy and Material Systems Lab (AEMS Lab) at the University of Canterbury, have been exploring issues of sustainability and energy-systems engineering in the social and environmental context. The AMES Lab projects propose that the evolution to sustainability requires two key elements of design and operation:

(1) A region-wide integrated energy and environment-system engineered for performance within resource and environmental constraints.

(2) A new economic relationship incorporating the system's physical and environmental realities.

The first element, design, could be built up of existing technologies, but would require a new systems-level fundamental understanding. In this paper, a fundamental model of a regional energy-system is presented. Applying this model in a systematic way would allow engineering analysis of complex systems, which include energy supply, consumer behaviour, government regulation, economic relationships and environmental impacts. The regional energy-system model can be used in much the same way that applying the First Law and thermodynamic principles allows design of a rather complex dynamic system like a heat pump from a collection of relatively simple individual components.

The second element, operation, would add new aspects of apportionment and communication of availability to the supply and demand economic relationship. This operation element arises from the soft system methodology (SSM) applied to the whole energy-system. Engineers inherently use this approach. For example, any graduate mechanical engineer understands that there is only one way to put together a compressor, heat exchangers and a throttle to make a heat pump. Operation of a thermodynamic system like a heat pump requires information, measurement and control at the systems-level. For example, the compressor, which increases refrigerant pressure, is not turned on in order to increase compressor consumption, but because a temperature measurement in the home was interpreted by a controller to mean that heat was required. In engineering, we understand that systems are not simply a collection of components. A system cannot be operated by simply observing the performance and adjusting the behaviour of any particular component. Optimal system performance depends on coherent operation of components, not independent best interest of components.

Regional electric energy-systems as well as other energy service systems, have been designed and are operated mainly from the component-level perspective. This approach is sufficient for operating an energy-system by supply and demand, as long as the capacity of the system far exceeds the demands put on it. A grossly over-designed system is not an efficient use of resources, although it may be reliable. If we accept for a moment that there may be limits to the investment in resource extraction and limits to the damage the environment can sustain, then we can see that a viable regional energy-system will be efficiently designed and effectively operated only if the resource and environmental constraints are incorporated into the economic relationship between suppliers and consumers. It is proposed that this new economic model would be based on desired service and resource availability as well as supply and demand. Customers would purchase services rather than simply energy commodities, and they would use information about availability to inform decisions about activities and consumption.

A system-level fundamental model of anthropogenic activity in the context of the energy infrastructure, economy and environment will be presented in this paper. This work also develops the argument that a more integrated economic relationship between environmental resources and customers is an inherent part of a sustainable system. The paper first reviews the disparate topics of economics and behaviour, energy-systems engineering, and control-system engineering. This is necessary to set out the language used, to make the case that economics and engineering separately represent component-level views, and to motivate the need for a systems-level model. Section 4 presents the regional energy-system model with examples and discussion. The model indicates that signals other than price must be part of a viable energy-system that operates within limits imposed by supply constraints and environmental impacts. In the final section, implications and opportunities of the energy system model are described and the proposed service and availability economics is argued to be necessary for sustainability.

3. BACKGROUND

3.1 Supply and Demand Economics and Behaviour

Economics is essentially a social science aimed at understanding wealth creation with the aim of achieving “economic growth”. A fundamental assumption is that human beings will fulfil their self-interest in a rational way with efforts directed at continuously increasing material wealth and consumption. Micro-economics aims to understand rational human behaviour and how people make choices of how to meet their wants and desires through choices about how to allocate their resources. Macro-economics can consider a regional or national level, but it can only include environmental, technological, or sustainability aspects through relation to price. In essence, economics focuses on understanding scarcity: how to achieve unlimited wealth and growth with limited resources.

The economic view of scarcity is actually different from the engineering concept of constraints or the ecological understanding of natural limits to resource extraction. Economics assumes that individual, business or national capital are constrained at any given decision point, and that decisions are made in order to maximize utility. In other words, you have a certain amount of money in your pocket and you have to decide how to maximize your satisfaction from consumption using the money you currently have. But economic does not recognize long-term or universal scarcity of raw materials or products. According to the law of supply and demand, if there is a shortage of products, then the price will increase and new producers will become willing to enter the market and the supply will increase. If the price rises higher than consumers are willing to pay, then a new supplier will enter the market with alternative products at a lower price. Thus, as long as customers desire or require a certain product or service, the free market will provide it and competition will ensure efficiency (Goodstein 2005).

On the supply side, the role of energy engineering in this supply and demand economy is to produce low-cost energy supplies (el-Wakil 1984, Patel 1999). Higher prices from local resource depletion stimulate new exploration, which leads to more supply, which leads to lower prices. Governments fund research into substitute fuels, such as biomass derived liquid fuels, which are expected to enter the market with the increasing price of oil. Oil companies develop more expensive enhanced oil recovery technology in anticipation of higher prices (Deffeyes 2001). Governments contemplate putting a price on environmental impacts, for example, a carbon tax because according to the law of demand, higher prices would reduce demand and thus reduce emissions.

A constraint event is a shortage of products imposed by the environment or by regulation to protect the environment and may be short- or long-term. For example, in the 1860s despite a high demand and high price for whale products, the animals had been hunted nearly to extinction and the quantity of whale products reduced. Of course, petroleum products soon replaced the scarce whale products. This idea of substitution, finding new resources or new technologies when current supplies run short, is prominent at present with discussion of biofuels, renewables and hydrogen as substitutes for fossil fuels. There does not seem to be any sense in the popular sentiment that demand must reduce simply because the environment cannot provide further resources. Although classical economics does recognise that supply shifts can occur due to natural disasters or other temporary constraint events, there is an underlying assumption that if there is unfulfilled demand, the market will provide through new suppliers.

The free-market idea of supply and demand does not effectively model services essential to wellbeing, like medical care and fire rescue, which are available in New Zealand to people regardless of income level. People would probably agree that a basic level of energy-services are essential to health and participation in society, for example, light for students to do homework, heat for health, cooking for sustenance, hot water for sanitation. When the electric energy supply system has surplus capacity, the price is low enough to provide services to all demographics. The higher electricity prices of the last decade have not resulted in reduced demand, but have caused disproportionate harm to small, lower income users.

3.2 Energy-systems Engineering

There are two primary roles of engineering:

(1) generate new assets
(2) maintain or improve the services and performance of existing assets

This distinction is vital to prospects for evolution to sustainability, because it seems only logical that societies cannot achieve a sustainable system by incrementally improving or reducing impacts of existing unsustainable systems. Improving energy efficiency does not necessarily mean that New Zealand's electricity system (with 43% fossil-fuelled generation) will be more sustainable. There is no fundamental principle of sustainability that can calculate the sustainability improvement achieved by uptake of compact fluorescent light bulbs. In order to understand sustainability and therefore to set targets for transition and improvements in a strategic way, some engineering effort must be focused on systems-level concept generation and feasibility modelling of truly sustainable systems, even if they are not currently conceivable or "economic".

The well-known methodology for development of design concepts is to first define the needs, wants and desires of the end users, then the system requirements and constraints. Concepts are generated through creativity and problem solving together with modelling based on fundamental principles and physical laws. Next, the concepts are evaluated according to performance and requirements metrics, and further design iterations produce a best-case concept. The final concept is then modelled and prototyped and further evaluated and developed according to requirements. In the end, a final design is achieved which provides the desired performance, within the cost and material constraints, and which obeys physical laws (Otto 2001). All products and systems follow this path into the market, with the notable exception of regional energy systems. Individual appliances and power plants follow the normal development process, but if we consider the whole energy system, including the end uses of electricity, transmission, and generation, we can see that it is considered more like an open system with inputs of natural or extracted resources and outputs of end use services as shown in Figure 1. As an example, consider a wind farm development. It harnesses wind resources which can only be economically exploited in certain locations and which vary unpredictably with time. A wind turbine interacts with the resource through aerodynamics and generates electricity while impacting the environment through land use and noise. The

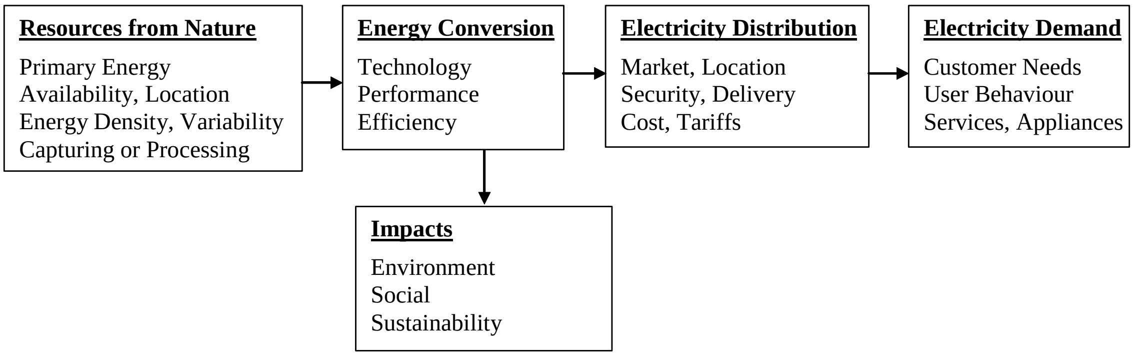

Figure 1: Energy flow diagram showing the development process for extracting or capturing a natural resource, converting it to electricity with the associated environmental impacts, distributing and marketing the electricity to meet demand.

electricity goes into the national grid, and must be immediately distributed to customers who may be using electricity to run a fan to move air.

Energy engineering after the OPEC oil embargo developed to include demand management, and new technologies to improve efficiency and save money on energy costs (Turner 1997, Weston 1992). A primary goal of energy management is to minimise energy costs through selection of high efficiency appliances and careful design and operation of energy consuming activities and processes. Another goal is to adjust operations and use new technologies to respond to price signals from electricity suppliers such as peak demand charges and time-of-day variable usage rates. These cost signals reflect the higher cost of peak power generation compared to base-load generation (Fardo & Patrick 1997).

Today's regional energy systems have been engineered as separate, rather autonomous components. Supply systems like hydro power plants or diesel generators work well according to their design. End use appliances like refrigerators and hot water cylinders also work well according to their design. The power grid is a dynamic system that continuously delivers the electricity from the generators to the end-users. Each component has a feedback control system. However, new system-level technologies and controls like ripple control and night rate switching, along with the associated economic instruments are increasingly required to maintain secure operation of the whole electric service system when there is a constraint on either supply or transmission capacity. For example, Christchurch has had transmission constraints for several years that pose a problem on cold winter evenings when heating loads are high. The local population has become accustomed to water heating and storage space heating that is replenished at night only through a night-rate controller on water cylinders. A lower rate for this time-controlled electricity is offered as the incentive for participation which is not mandatory.

Energy efficiency is a characteristic of energy conversion, transmission and end-use appliances, but it does not provide any real-time control mechanism that can provide security of the supply system during constraint events. For example, higher efficiency water cylinders may reduce total consumption, but they do not reduce the winter-afternoon peak demand in Christchurch if they are already on a night-rate circuit. Energy conservation refers to adjustments in consumption patterns to reduce waste or reduce services. Again, conservation may reduce energy use, but is not necessarily a direct control that can be used to manage constrained supplies or environmental impacts to achieve sustainability.

In the future, as new constraint events are anticipated, new integrated, systems-level control mechanisms will need to be developed, including new modelling capabilities for suppliers, new information systems, and new communication and control technologies at the point of use. In addition, new economic instruments will be required which complement each regional energy-system control mechanism in order to broker participation. It may also be possible that social-level demand response

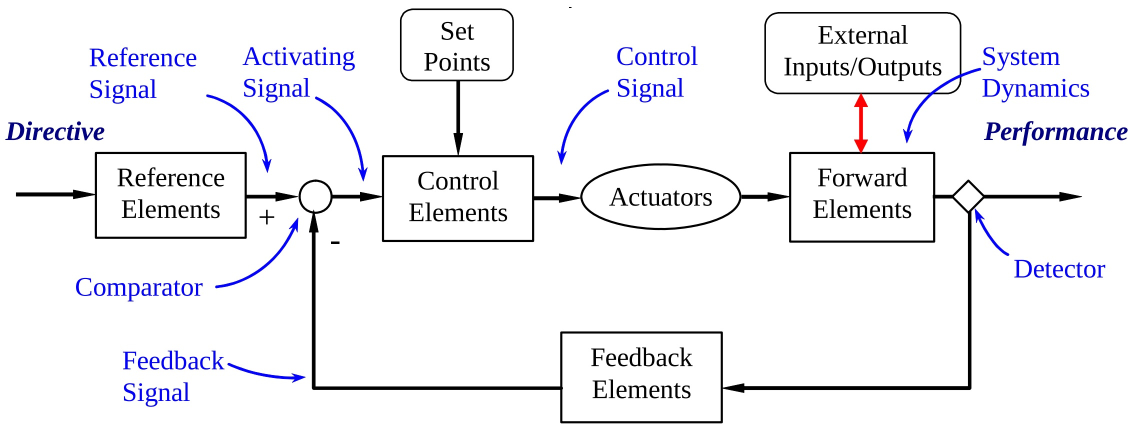

Figure 2: The standard representation of a feedback control system, which is continuously controlled by the control elements so that the performance achieves the directive

strategies will be useful. This type of social-level response was used during the last dry year when a government information campaign asked the population to reduce electricity use by 10 per cent.

3.3 Control System Engineering

Modelling, analysis and control of dynamic engineering systems are accomplished through application of control system theory (Palm 2000, D'Azzo & Houpis 1981). Control systems maintain the designed operation and system stability. The system controls can only keep the physical system working as desired as long as the operational parameters of the system are not exceeded. How well a system responds to disturbances in individual element parameters and to feedback parameters is a measure of the robustness and reliability of the system. The control system theory is a fundamental representation of dynamic system behaviour, which can be applied, in principle, to mechanical, electrical, biological and ecological systems.

Figure 2 shows a basic block diagram describing a control system. There are various configurations for such a block diagram model, depending on the particular system of interest, but this representation includes most features according to the standards of the IEEE. With the exception of the external inputs and outputs, the arrows in the block diagram do not represent flows of materials, but are communication signals between dynamic elements. The control system is an integral part of a continuously operating dynamic system, for example a cruise control system on a car travelling on a freeway.

The directive represents the motivating input to the system. It is independent of the actual performance, but expresses the required condition for system performance. The reference elements establish the values of the reference signal calibrated for a particular system in a particular situation. The reference signal is the particular form of the directive, which is directly useful to the system. The comparator performs the function of determining if the reference signal is equal to the feedback signal. If the signals are equivalent, then there is no change needed in the system in order to meet the operational directive. Changes can occur for other reasons, but no changes are necessary. The activating signal to the control elements is used to determine operational changes that will push the system performance toward the reference signal values. The control elements generate the control signals according to the magnitude of the activating signal and according to pre-existing control design, strategies and other set points. Control actuators cause physical changes, through existing physical mechanisms and actuators. Forward elements represent the physical plant and the system dynamics that react to the actuators and affect the performance of the system. The performance is measured by detectors and represents the actual system behaviour. Feedback elements translate measurements of the system performance into the feedback signal, which has the same calibration as the reference signal and thus can be used by the control elements to attenuate the system behaviour.

In the example of an automobile cruise control system, the directive would be the desired speed set by the driver, the performance would be the actual speed, the set points would be relationships between controller signals and automobile dynamics, the actuator would be the fuel supply throttle and brake fluid and the external inputs would be fuel and air. The forward elements would be the entire vehicle, including the engine thermodynamics, transmission, aerodynamics and wheel-tire friction with the road. This example illustrates how important the signal processors are in sustainable operation of a system. The driver sets the directive of a desired speed as safe and sustainable for the present driving conditions. That information cannot be used by the microprocessor in the car unless it is first processed into an electronic reference signal. The measurement of vehicle speed is achieved through a transducer that produces an electronic signal that would not be recognized by the driver as speed unless that signal is processed through calibrated electronics, such as a Wheatstone bridge, and then sent to a speedometer to actuate the indicating needle. Another important concept is that the controller acts in predictable ways in response to the control signal, which is not the actual speed, but the difference between the reference and the feedback signals. The cruise control system for a given automobile was designed and calibrated and the microprocessor controller was programmed according to the automobile specifications. It is vitally important to understand that the controller can only actuate the system according to the existing design and cannot operate the system in a way to change its design.

The next section proposes that the engineering and economics of sustainable anthropogenic systems can be understood by modelling the regional energy system as a feedback control system. If this theory proves correct, then the nature of the system design, measurements, flows of information and the economic relationships will be important areas for study and research.

4. REGIONAL ENERGY SYSTEM MODEL

4.1 Fundamental Form of the Theoretical Model

The term “regional energy system” refers to the entire supply and distribution infrastructure (hydro scheme and transmission system), the individual energy-consuming devices (heat pump), the people of a geographic community who receive a desired service (indoor comfort and health), and the environment which both provides the resources and receives the impacts (rivers, ecosystems). Obviously, a regional energy system is complex and diverse. A fundamental model can be applied to particular subsystems, to individuals or to aggregate populations. A region is defined according to social, infrastructure and environmental coherence, but the definition of the regional energy-system boundary can be made as necessary for any particular analysis. At a regional energy-system boundary, energy and resources in different forms may flow in or out and must be accounted for. Because the model uses a fundamental concept, it can be applied to any system. Deciding where to designate the system boundary would be made in much the same way as in any other engineering analysis.

It is important to note that the model was developed largely by examining the behaviour and dynamics of cultures from around the world and from different points in history. The theoretical model is a general description of an anthropogenic system irrespective of social structure, type of government, economic philosophy, or technological level. The model describes the structure and behaviour of a continuous anthropogenic system at any particular point in time. Civilizations that have maintained a particular infrastructure, resource consumption and activity level for several hundred years without unsustainable impact on the environment can be seen to have a robust, high-stability system, with all of the components and signal pathways working effectively. Societies that have collapsed due to environmental exhaustion can clearly be seen to have dysfunction in some part of the system.

Figure 3 shows the general form of the regional energy system model. The model was developed by considering the dynamic behaviour of

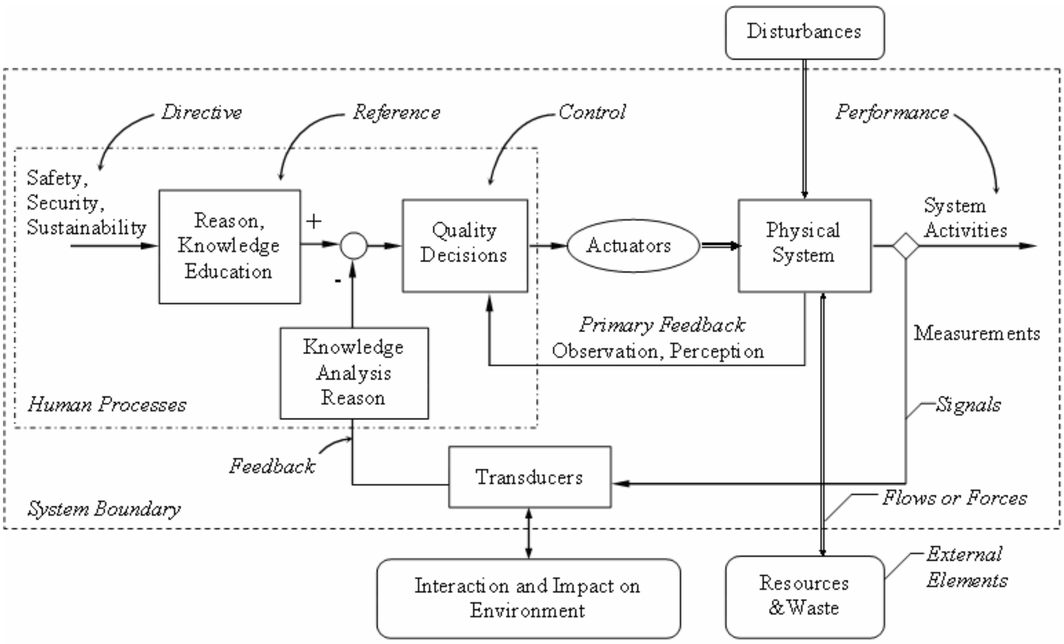

Figure 3: The regional energy/environment/economy system model showing the role of the economy as an actuation element in the system, rather than as a control element. Sustainability is part of the reference signal, meaning that system elements must change if the system activities representing the performance do not meet the sustainability condition. There are three levels of feedback: availability, performance, and environmental impacts. System control is accomplished through the cumulative individual decisions made in the cultural, regulatory, and economic context.

anthropogenic activities according to control system theory (Krumdieck 1989, Krumdieck & Wood 1989). Figure 3 represents a feedback control model, not an input-output flow model. The arrows represent information, connections or actions, not energy or material flows, except for the system resource inputs and environmental impacts. We define the system as any community of people, their relationships with each other through economic activities, the infrastructure that they use in these activities, including appliances, buildings, etc. within a given environment and resource setting. The model represents the dynamics involved in carrying out the society's activity systems at any point in time. If the technology, built environment or resources change, then the system has changed, and a new model will be needed to describe the dynamic behaviour of the new system. The factors that cause change in the infrastructure or technology may be understood through the system analysis, but the control model theory applies to a particular physical system. Consider the example of the automobile cruise control system. The same control theory model would apply to either a Holden or a BMW. However, the particular system model for each vehicle design would be unique.

4.2 System Operational Directive

The directive for society represents a shared cultural vision that transcends any details about the actual resources used, technology or any particular activities. By logical deduction, if the regional energy system is safe, secure and environmentally sustainable, then it can continue year-after-year. The high-level concepts of safety and security are already part of the energy engineering requirements, with sustainability becoming more of a consideration.

4.3 Reference Signal

The reference signal represents sustainable resource consumption and environmental impacts of a particular community carrying out their normal activities using particular technologies. The higher-level directives are processed into the specific reference signal by means of the knowledge, reason and education of the society. In other words, determining a sustainable, safe and secure level of consumption, and impacts to support a certain level of activity would require a concept-level system model for a specific region employing some specific set of technologies. There are currently methods to assess the safety risks of appliances and the security of the electric supply system. However, there is no currently available method for quantitative sustainability assessment. The AEMS Lab is working on research to develop metrics and analytical methods to assess sustainability of regional energy system concepts. The system model indicates that this capability will be vital to future societies that aim to be sustainable.

The reference essentially answers the question: “What would a sustainable society in this region be like?” Many ancient societies had well established and effective reference signals which allowed them to understand their relationship with natural systems. Of course, they developed this knowledge through generations of observation and experimentation under conditions of incremental change. The Anasazi civilization of the Southwestern United States maintained a civilization of dry-land farming of squash, maize, and beans, together with hunting and gathering of wild foods for nearly 700 years with almost no technological or resource consumption change (Rohn 1971). Paleoanthropologists believe that the Anasizi, like most North American aboriginal people, had culturally integrated ideas concerning the use and allocation of natural resources. Their “way” of carrying out their activities was taught to new generations as part of a long tradition of what works in a particular environment. Interestingly, different tribes throughout the vastly diverse environments of the continent developed unique technologies and patterns of life, but all had the same reference of sustainable cultivation and harvesting methods. This is particularly evident when the indigenous cultural vision is compared to the development-oriented vision of Europeans.

4.4 Feedback Signals and Comparator

There are usually several different feedback signals in control systems. In the regional energy system model the two main feedback signals are designated as primary and general. All people make use of primary feedback directly and continuously to function effectively. This primary feedback includes observation and learned knowledge about price, convenience and utility. For example, people may know from experience, advertisement or public information about the cost and performance of various heating methods. The primary feedback is the main source of information for system control because it relates directly to particular activities. The general system-level feedback represents information about the aggregate impact of activities on the environment. This information is usually not directly related to any particular actions by individuals. For example, the variation of river flows to match electricity demand from hydro generation has been shown to have an impact on riparian ecosystems. This is an aggregate effect which is caused by consumption behaviour, but currently this information has no mechanism for changing behaviour.

The comparator continuously evaluates feedback of actual measured consumption and impacts against the reference levels. In electronic systems, this is done by subtracting the feedback signal from the reference signal. Obviously, this type of analysis would require continuous monitoring of resource and environmental systems in relation to human activities together with knowledge of sustainable levels of consumption and impacts. It is simple to see how this would have worked for sustainable pre-industrial societies. The traditional knowledge of how to carry out activities in a sustainable way would have been a strong, shared cultural vision, and the impacts of people’s activities on local resources would have been observable and understandable to people who relied on those resources for survival. In his recent book, *Collapse*, Jared Diamond (2005) sets out the theory that some societies choose to continue activity systems that lead to environmental collapse even though the problems must be observable. The regional energy system model can be seen to accurately represent this type of behaviour. For example, Diamond describes the behaviour of the Greenland Viking colonists who continued their shared cultural vision of behaviour and resource use, even though it did not fit with the Greenland environment. He explains that in a land teeming with fish, the people starved to death rather than break with their traditions as cattlemen and hunters.

At this point, it may be evident to the reader that our modern society is in a similar quandary, where our shared cultural values and vision are not reconcilable with environmental sustainability. The public are receiving more and more feedback information about global climate change, for example, but that information does not have any cultural reference of a non-globally destructive activity system and so the information produces no signal to activate the controller to bring the system back into a safe, secure and sustainable mode of operation. Electronic measurement signals in the cruise-control system are processed into signals like vehicle speed which can be compared to the set speed. In the same way, ecological and environmental monitoring must be processed into information that is directly related to daily activities and which is relevant to known sustainable conditions. Clearly, there is a great opportunity and necessity for development within our society in this area.

4.5 Control Elements

If the system is not performing according to the reference, then the controller determines changes in operation or forward element parameters which will correct the problem. The controller for this system is an aggregate of the decisions that individual people or groups make on a continuous basis, given their existing knowledge and experience about what actions will provide a quality of life. An important input to these decisions is the primary feedback of their own perceptions and observations. For example, people have knowledge from their previous experiences of how to successfully carry out their activities. This body of learned knowledge together with analytical capabilities provides essentially the same function as the electronic microprocessor in the cruise control system. The controller is pre-programmed with the system signals, and how to adjust fuel flow or apply braking in order to maintain the set speed. In the same way, individuals, and in the aggregate, the society has a predetermined set of rather routine activities, and sufficient information and decision-making capabilities to manage variations in the patterns of daily life.

A person's daily routine is essentially a set point. Our daily routines are formatted within the rules of governance and social behaviour of our society, and use technologies and energy supplies which are already available. Except for extreme cases of totalitarian governments, the rules and regulations, and acceptable social behaviours are to some degree, expressions of the shared cultural values. This view of system control may represent a radical departure from the supply and demand economics view. The control theory indicates that people's rational behaviour today is based mostly on the activities that were successful yesterday in meeting their needs. The primary factor in determining behaviour is what people already know, not increasing their satisfaction through consumption.

This type of control is true for any manifestation of built environment or technology level. In the control system model, it is conceivable – indeed it is imperative – that demand be controlled to match a safe, secure and sustainable supply.

4.6 Actuating Elements

The cumulative activity in a community results in a distribution of lifestyles, and activities. All of the community activities involve economic participation. For example, people's ordinary behaviour is to heat their homes in the winter for comfort and health reasons. In Christchurch, there is a wide variety of heating technologies in use, and a range of indoor temperatures achieved. Homes with night-store electric heaters consume electricity that is purchased at a lower cost than homes that use a heat pump. In any case, all homes achieve the type of heating they routinely employ through purchasing electricity from a supplier. Thus, economic relationships between providers and consumers act as the actuating elements of the system. Popular opinion might be that cost drives people's decisions about consumption. However, the control system model indicates that economic relationships are actuators that determine how people access the goods and services they decide to purchase to meet their needs and quality desires, not the reason they have desires or participate in activities. There may someday be information about the resources being used to provide the electricity, and people may develop a reference vision of minimizing evening peak loads to maintain secure supply and eliminate the demand for fossil-fuelled generation. If this happened, people might choose to fire up their clean burning wood appliance or use the night-store heater rather than the heat pump during peak times, even though the heat pump is highly efficient. They might do this based primarily on the reference information, and not on cost.

4.7 Forward Elements of the Physical System

The physical system represents the generation technology, transmission circuits, appliances, and built environment that the community uses in the course of going about their normal activities. Some things like power plants and school buildings have collective uses, and others, like heat pumps and refrigerators are used by individuals or households. If the built environment were designed to function within resource and environmental constraints, then people's daily activities and decisions would be within the context of a potentially sustainable system, and their pursuit of individual desires within a free market would not necessarily threaten the environment (Binswanger 1998, Neumayer 2000).

We have already established that people learn what works to support their activities in a given built environment, and then act rationally by using what they have learned. For example, a New Zealand tourist in Paris, would quickly learn that driving a car is not a successful way to go out for a meal compared to walking. However, in Christchurch, most people drive to the city or take a cab for a night out because it works well. When we walk down the street to find a café in Paris are we doing it to increase our utility, or because of the cost, or out of a sense of environmental responsibility? Or are we simply behaving rationally given the physical system we are in? The point is that the built environment and the technology that already exist at a given time determine the behaviour of the population.

4.8 Flows Across the System Boundary and Disturbances

The activities of people in a region require material inputs from the environment both inside and outside of the system boundary. The activities in the region may also produce products and wastes that move across the system boundary. Control system theory deals with these externalities as material inputs and outputs to the physical system. For the cruise control system example, the level of fuel in the tank is not a part of the speed control system. However, the constant speed can only be maintained as long as the flow of fuel continues to flow to the engine. The sustainable supply and export of resources would need to be determined based on the source or sink environments.

Activities and technology can change in many ways, which we term disturbances, even though the changes may include innovation and technology development. At any given time, the existing built environment and appliances are used as intended – people prepare their dinner, children read books, shops provide goods, milk is processed etc. If a new regulation, a new behavioural pattern or a new technology becomes part of the system, then it has essentially disturbed the original system.

5. SERVICE AND AVAILABILITY CONTINUITY ECONOMY

The control theory model shows that there must be a balance of desires of the consumers against environmental sustainability constraints. This hypothetical service and availability economic behaviour has been proposed to provide the appropriate actuation functions in the regional system model. In this model, the normal free market and supply and demand pricing would operate within the context of the services individuals require for wellbeing and the real-time availability of resources.

This type of economic model is already employed where the desired energy service is constrained. One example in transportation is the airline booking system. If we had the same kind of system for air travel that we do for electricity, then flights would have to be available on demand. That would mean that people would arrive at an airport and have access to flights to the destination of their choice. It is not possible to have airline flights on demand, the number of flights to each destination on any given day is constrained. The airline reservation system is a service-and-availability economic relationship, rather than a supply-and-demand economic relationship. Customers first check on availability of flights to their desired destination and evaluate costs and possible times. They then purchase the service that best suits their requirements. Airlines can also use the information about the flights that people choose in scheduling their services to make efficient use of resources. No one considers the airline reservation system to be a form of rationing, although it is an effective way to apportion a limited supply. People have learned how to participate in service-and-availability economic relationships with popular restaurants and other venues where supply needs to be queried before services are demanded.

In the case of electricity supply or fuels, constraints may be due to supply variability or due to local or global emissions. There are no examples of service-and-availability systems in these markets, but we do point it out as a possible area for innovation. Night-rate and ripple-control mechanisms are automatic load-control systems that do not require query of availability by consumers. They provide a similar function, however, adjusting demand to match available supply and avoiding blackout of the supply system.

5.1 Implications

It is not the purpose of this work to suggest incremental improvements to the current energy or policy system in New Zealand. Rather, the regional energy system model suggests that one of the first necessary steps for understanding the implications of sustainable energy is to carry out engineering concept generation of sustainable regional energy systems as points of reference. The beginning point for any transition to sustainability is both qualitative and quantitative understanding of natural resource and ecological constraints.

Many people perceive the inevitable demise for our present energy system through depletion of low-cost resources (Heinberg 2003) or the collapse of social and environmental support systems (Tainter 1988). The “tragedy of the commons” parable expresses the age-old idea that individual self-interest will lead to over-exploitation of shared resources (Hardin 1968). However, Diamond (2005) gives examples of several societies that have established activity patterns that continuously use limited resources without destroying their environment. The regional system model shows how both tragedy and continuity can occur.

We have already proposed that individual self-interest is a function of the controller for the system. Any mechanical or electrical feedback-controlled system can be unstable if any of the necessary elements (signals, signal processors, controller) are not available, or if they are designed incorrectly. The classic example is an under-damped system or a system where one component has an uncontrolled gain. A society without a shared cultural vision of sustainability expressed as resource and environmental limits will essentially accept uncontrolled consumption growth behaviour much like bacteria or algae. Both organisms grow rapidly when resources are abundant and decline when resources are depleted. A society that values and understands the requirements for sustainability would not be able to achieve it if they did not measure or understand their impacts on the environment. If the reference and feedback signals are missing from the system, then indeed, the self interest of individuals will not be moderated with the higher-level directives, and the tragedy of the commons will occur. The regional system theory fits well with Diamond’s observations that some societies choose to engage in activity patterns which are not sustainable. In this paper, there is no theory presented about how some societies come to have institutionalised reference and feedback mechanisms for sustainability, or how they developed sustainable built environment and technologies.

5.2 New Opportunities

Analysing the regional energy system model suggests that there are new opportunities for technology, infrastructure and information systems development. Engineering for sustainability is not limited to reducing costs, increasing efficiency, developing alternative energy resources or fixing pollution and congestion problems. The system model has been used to understand existing systems, develop understanding of current problems, and to develop strategic solutions to current issues. The problem of home heating and winter air pollution in the context of a constrained electric transmission grid in Christchurch has been studied (Krumdieck 2004). The analysis resulted in a new solution to an old problem which was politically, socially, and economically viable as well as sustainable and secure with respect to energy and safe with respect to health. A sustainable energy concept has been developed for a public transportation route in Christchurch (Dantas et al 2004). The system model has also been the basis of a new transport planning methodology developed to include energy constraints in transport security analysis (Dantas et al 2005).

The following research areas indicated by the regional system model are being pursued by the AEMS Lab:

(1) Understand sustainability both as a shared cultural vision and as a quantitative concept generation of physical systems that have sustainable resource consumption and environmental impacts.
(2) Understand the economic relationships in a sustainable New Zealand regional society and developing new information communication technology (ICT) concepts that could facilitate the service and availability economy.
(3) Characterise, measure and monitor the environment and sustainable resource availability.
(4) Develop concepts for technologies that could provide relevant real-time feedback to individuals and groups which elicits a necessary demand response, ie adjusting demand to meet supply.
(5) Engineer design methodologies and technology innovation to develop sustainable regional energy systems.

6. CONCLUSION

In New Zealand, many people express the desire to be more sustainable, efficient or environmentally friendly. The clean green image is a pervasive cultural icon. However, we don't have a concept of what New Zealand would be like if we actually were sustainable. Without a reference point of what we mean by sustainability or what our energy use and environmental impacts would be if we were sustainable, then we have no way to use feedback about energy or environment to make decisions that would lead to sustainability. While we do have feedback in the system, only the primary feedback about what works at a given moment has direct relation to decision making. Other feedback about situations like global climate change or variability of renewable resources do not have immediate feedback and control mechanisms to adjust activities to ensure security of supply without causing irreversible damage to the environment.

The theoretical basis of feedback-control systems has been applied to regional energy/economic/environment systems to produce a dynamic model of anthropogenic activity. While the proposed model in no way represents a means to "design" the future, it provides a fundamental model to explore sustainable energy system concepts. The regional energy system model points out several important features of a sustainable society that the current New Zealand system is lacking.

The first is a reference model of the high-level requirements of safety, security and sustainability and how they can translate into particular consumption and impact rates for a given region through conceptual modelling. The second is a feedback monitoring and modelling capability that provides continuous measurement of anthropogenic consumption and impacts and provides appropriate information for comparison with the reference model. Part of this feedback capability would be a means of communicating individual level information about aggregate impacts. Finally, the control-system model shows us that no amount of economic incentive, education, desire or behaviour change can make an unsustainable system more sustainable. Sustainability of regional energy systems that support human endeavour cannot be achieved through technology upgrades of systems that are designed for fossil fuel consumption and operated through an economic model aimed at continuous growth of consumption. The infrastructure, built environment and operation of the physical system must be designed for sustainability. Security and sustained wellbeing will require integrated system design, which considers the service required, and the availability of primary resources and environmental carrying capacity.

Thus, the role of engineering in achieving sustainability must be to work in an integrated way within the social, economic and political context, using the regional energy system model as an integration modelling and design tool. New areas for ICT development will lead to implementation of new decision-making methodologies commensurate with a new economic model that incorporates resource availability and shared cultural vision of safety, security and sustainability.

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