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Article

Evaluating the Use of an Integrated Approach to Support Energy and Climate Policy Formulation and Evaluation

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Abstract: With the adoption of the Kyoto Protocol in 1997 national leaders have started investigating options for reducing carbon emissions within national borders [1]. Despite confronting similar energy issues, every country that adopted the Kyoto Protocol has a unique energy strategy [1,2] -being characterized by a different context, social, economic or environmental that influences the way different nations deal with climate change and other energy-related issues. Finding that currently available energy models are often too detailed or narrowly focused to inform longer-term policy formulation and evaluation holistically [3], the present study proposes the utilization of an integrated cross-sectoral medium to longer-term research and modeling approach, incorporating various methodologies to minimize exogenous assumptions and endogenously represent the key drivers of the system analyzed. The framework proposed includes feedback, delays and non-linearity and focuses on structure, scenarios and policies, requires a profound customization of the model that goes beyond a new parameterization. The inclusion of social and environmental factors, in addition to economic ones, all unique to the geographical area analyzed, allows for a wider analysis of the implication of policies by identifying potential side effect or longer-term bottlenecks for socio-economic development and environmental preservation arising from cross-sectoral relations.

Keywords: energy policy; integrated modeling; T21

1. Introduction

With the adoption of the Kyoto Protocol in 1997, national leaders have started investigating options for reducing carbon emissions within national borders [1]. After ten years debating about whether the global and national economies would have been negatively impacted by the implementation of such measures, rising global concerns on climate change have urged policy makers to find ways to reduce the carbon intensity of the global economy [2].

The present study aims at providing insights on the complexity of the systems analyzed, reviews the methodologies and models currently used to support energy policy formulation to propose an integrated approach. A reflection on its validation is proposed and a case study, using a model that bridges various methods and methodologies, is also presented, before thoughts on the needs for further research are introduced.

The main motivation for the present study stems from the acknowledgement that there is a need for integrated tools [3] that could serve as a mean to close the gap between dynamic and all embracing thinking, which is required when facing critical issues such as the upcoming energy transition and climate change, and available conventional modeling tools (e.g., optimization and econometric models). Despite confronting similar energy issues, every country is characterized by a different context, be it social, economic or environmental [4], that influences the way different nations deal with climate change and other energy-related issues [3,5]. Energy issues should therefore be contextualized to effectively support policy formulation and evaluation [1]. This implies (1) the analysis of the context in which energy issues arise, whether they are global, regional and national, and (2) the study of various policy options that are being considered for solving energy, environmental and national security issues [3,6]. While the analysis carried out with conventional linear programming and optimization models is limited by narrow boundaries and lack of dynamics [3,7], computer simulation models based on System Dynamics could effectively support the analysis of both context and policies [8]. The use of these tools, such as Millennium Institute's Threshold 21 (T21) energy models [3,5,9–11], provides an integrated analysis of the following characteristics of the policy-making environment:

- Despite energy issues being global, regional and national, policy solutions are designed and implemented at the national level [1,3].
- Despite interconnected and cross-sectoral energy issues, policies are narrowly focused on the energy sector while having an impact on society, economy and environment [3,5,6].
- The political context, often excluded from quantitative studies, is an important factor influencing policy effectiveness. A participatory approach is needed to understand the political context and create trust between modeler and policy makers [3,12].

Modeling the context in which energy issues arise in this research work involves:

- Studying global, regional and national issues and the understanding of how they impact domestic energy policy formulation.
- Incorporating energy, society, economy and environment into a dynamic modeling framework.
- Building models that serve to create dialogue and establish a mutual trust relationship with policy makers and stakeholders.

The following sections provide an overview of the characteristics of geographical energy contexts, present an overview of methodologies and existing models, and introduce the novel approach proposed. A case study is then presented, followed by conclusions.

2. Underlying Characteristics of Geographical Energy Contexts

Energy contexts are unique in different geographical areas. Properties ranging from political environment to richness of natural resources characterize these contexts. When reducing them to a simulation models, boundaries are set. In order to represent the diverse properties of the system, customization is needed. In addition, given the numerous interrelations existing among society, economy and environment, complexity has to be simplified to account for the key mechanisms influencing the course of events.

Different geographical areas can have similar characteristics and show similar behavior while being structurally different. To better understand how the underlying structure of the system generates its behavior longer term integrated energy models should decouple the properties of the real social systems analyzed. Reality is complex, for two reasons: there is a very high level of detail in every real system (*i.e.*, every major process is built up on smaller ones, that contribute to the formation of the aggregated behavior of the system), and there are dynamic relationships existing among both the elements forming the system analyzed and the ones surrounding it. While conventional modeling tools can extensively represent the details of each linear process involved in a real system (e.g., energy transformation from crude oil to refined fuels), a closer investigation of the dynamic relationships contributing to the growth and progress of the system itself is needed. Real dynamic systems are characterized by feedbacks, non-linearity and delays. These properties may unveil the existence of policy resistance mechanisms that greatly influence behavior and are often responsible for the manifestation of side effects -among others, limiting the effectiveness of policies.

"*Feedback is a process whereby an initial cause ripples through a chain of causation ultimately to re-affect itself*" [13]. The energy policy in place in Saudi Arabia provides a good example of a feedback loop that can be found in real life. In order to distribute the profits of oil exports, the government has decided to further subsidize domestic gasoline prices as world oil prices increase [14]. This mechanism helps keeping social cohesion and government support. On the other hand, this intervention generated a series of side effects: lower domestic price of gasoline translated into higher domestic consumption; when domestic consumption increases, all else being equal, exports have to decrease, as well as profits. In order to mitigate this negative effect, since crude oil is normally exported to be refined by foreign companies, Saudi Aramco, the national oil company of Saudi Arabia, is planning on increasing domestic refining capacity to avoid paying a premium price to foreign refiners and maximize the -reduced- profitability of domestic production.

The example above identifies a negative feedback loop, where high profits lead to a decrease of future profitability due to increasing domestic demand. Such loops tend towards a goal or equilibrium, balancing the forces in the system [15]. A feedback can also be positive, when an intervention in the system triggers other changes that amplify the effect of that intervention, reinforcing it [15]. This is the case of production from an oil field, before reaching a plateau phase: the higher the investment in production capacity, the higher the production, thanks to high pressure in the reservoir; likewise, the higher the production, the higher the revenues, and therefore investments in production capacity and production.

Real systems are often characterized by the simultaneous presence of interconnected reinforcing and balancing loops [15]. This is the case of oil production again, where recovery increases depletion and lowers pressure in the reservoir, creating a balancing loop. This loop regulates the plateau phase of production and its decline, and becomes dominant after the reinforcing feedback involving discovery and recovery in the early stages of production has generated exponential growth in extraction. Increasing investments in exploration and recovery in this case do not allow the reinforcing mechanism to be sustained over time and increases production rates further.

By linking the energy sector to other dimensions of society, economy and environment, feedback loops contribute to the representation of the context in which different energy issues are analyzed. Using feedback loops and wider boundaries to analyze energy issues allow the identification of side effects, elements of policy resistance, and eventually synergies that would make policies more effective. For instance, simulating improved Corporate Average Fuel Economy (CAFE) standards in isolation indicates decreasing future consumption of motor gasoline. Adding feedbacks helps to identify an important element of policy resistance: reducing consumption of motor gasoline decreases households' expenses making more resources available, which in part will be spent, saved or invested, thereby stimulating economic growth and increasing energy consumption. This feedback identifies an element of policy resistance and allows the anticipation of what is known as Jevons Paradox [16], or rebound effect [17,18], applied to the US transportation sector and CAFE standards.

When formulating policies it is very important to take into consideration time delays, "*a phenomenon where the effect of one variable on another does not occur immediately*" [19]. These can in fact lead to instability, such as overshoot and oscillations, when coupled with balancing processes.

Since delays influence the efficacy of policies in both the short and the longer term, their explicit representation generates many advantages. First, integrated complex systems are dominated by inertia in the short term, therefore the implementation of policies does not produce immediate significant impacts. As Jay Forrester states "*A system variable has a past path leading up to the current decision time. In the short term, the system has continuity and momentum that will keep it from deviating far from an extrapolation of the past"* [20]. Secondly, when the short-term performance of the system is negative or below expectations, often the case when costly interventions are implemented, policy makers tend to change direction hoping to move towards their desired goal. The outcomes of such shift tend not to be encouraging due to both the additional implementation cost and the lack of short-term positive outcomes (again due to the inertia of the system). Such a strategy, very common in our present political structures and mainly driven by short-term pressures and agendas, prevents the system from (1) effectively adjusting to the proposed interventions and (2) improving over the longer term. Most policy proposals that are indeed focused on short-term interventions have few longer-term impacts. Thirdly, representing delays helps identify side effects and elements of policy resistance that usually emerge over the medium and longer term. For this reason a longer time frame of analysis is needed.

Representing the structure of geographical energy contexts and delays characterizing it allows therefore to estimate both short and longer term implications of policies, while supporting the elaboration of needed mitigating actions that allow the system to move in the desired direction (e.g., when the cost of positive longer term interventions creates short term negative consequences).

There are many instances in which delays can strongly influence the behavior of a system. These include for instance the way world oil production is approached. According to the Hirsch Report [21], mitigating the peaking of world conventional oil production presents a classic risk management problem, which is also characterized by delays. Mitigation measures taking place well in advance the event of declining world oil production may be premature and expensive. On the other hand, if actions were taken only after world oil production starts declining, society, the economy and the environment would be exposed to major (and bigger) challenges. It has to be considered that a prudent approach would consist in taking actions earlier rather than later, as early measures will almost certainly be less expensive than delayed ones.

Complex systems are characterized by non-linear relationships that cause feedback loops to vary in strength, depending on the state of the system [22]. In systems built on a variety of feedback loops, non-linearity creates shifts in dominance of such loops, which become very important in determining how structure defines behavior, even at different times and with different states of the system.

Non-linearity allows for a clearer interpretation and understanding of the context of analysis. In fact, non-linearity is a very important instrument when investigating events that cannot be found in our recent (or measurable) history. A wide range of scenarios with different assumptions on non-linear relations existing within the system can be simulated to test and evaluate the impact of various policy choices. An example highlighting the importance of non-linearity is the recent increase in oil prices and its impacts on consumption. Such a rapid increase in oil prices may be perceived in different ways based on the actual status of the economy (system analyzed). Non-linear relations highlight the creation of ruptures as well as stronger or weaker approaches in response to unprecedented issues. Though this approach may not be perfectly accurate, it provides insights on the potential medium- to longer-term impact of policies that cannot be discerned from linear tools.

Both dynamic and detailed complexity should be represented to reach improved understanding of the context in which issues manifest themselves and have to be faced. Combining feedback loops, non-linearity and delays contributes to the creation of a consistent and coherent framework for the analysis of the properties and structure of complex systems. When considering a specific example, such as the one of the application of improved CAFE standards, feedback loops identify elements of policy resistance, non-linearity supports the analysis of consumer behavior in response to energy prices and private spending, and delays contribute to the analysis of both short-term (positive) and longer-term (negative) implications of increased CAFE standards.

3. Methodologies Review

The strengths and weaknesses of a methodology applied to integrated energy modeling depend on the specific characteristics of the methodology (its foundations) and on the issues being analyzed (its application). For instance, when projecting longer-term energy scenarios, using exogenous assumptions on population and economic development may lead to an inaccurate analysis [23]. Optimization, econometrics and simulation are presented, with emphasis on how they account for the complexity of the system analyzed. A more detailed comparison of models used for supporting energy policy formulation and evaluation follows.

Optimization models, which generate "a *statement of the best way to accomplish some goal*" [7], are normative, or prescriptive, models. These models provide information on what actions to take to make the best of a given situation (the actual one). Optimization does not provide insights on what might happen in a particular situation or what the impact of actions may be. Policy makers often use optimization models to define what the perfect state of the system should be in order to reach the desired goals -information that allows them to formulate policies intended to reach such a perfect state of the system and, ultimately, their goals.

In order to optimize a given situation, these models use three main inputs: (1) the goals to be met (*i.e.*, objective function), (2) the areas of interventions and (3) the constraints to be satisfied [7]. Therefore, the output of an optimization model identifies the best interventions that would allow reaching the goals (or to get as close as possible to it), while satisfying the constraints of the system [24,25].

The challenges related to optimization models include the correct definition of an objective function, the use of linearity, the lack of feedback and lack of dynamics. Such models usually do not provide forecasts, but some of them such as MARKAL [26,27] and MESSAGE [24,25] provide snapshots of the optimum state of the system with yearly -or longer- time intervals. Such models use exogenous population and economic growth rates, among others.

Optimization models can be very useful in defining the optimum solution (target) given a specific situation, on top of which specific policy proposals are formulated. Optimization can also be applied to issues and systems that are relatively static and free of feedback. Such properties can be found in analyses focused on the short-term or on controlled environments.

Econometrics measures economic relations, running a statistical analysis of economic data and finding the correlation between specific selected variables. Econometric exercises include three stages—specification, estimation, and forecasting [7]. The structure of the system is specified by a set of equations, describing both physical relations and behavior, and their strength is defined by estimating the correlation among variables (such as elasticities, coefficients relating changes in one variable to changes in another) using historical data. Forecasts are obtained by simulating changes in exogenous input parameters that are then used to calculate a number of variables forming the structure of the model (e.g., population and economic growth).

The most important limitations of econometrics are related to the assumptions characterizing the most commonly used economic theories: full rationality of human behavior, availability of perfect information and market equilibrium. When looking at the results produced by econometric models, issues arise with the validation of projections (that cannot backtrack historical data) and with the reliability of forecasts that are only based on historical developments and on exogenous assumptions. As a consequence, the analysis of unprecedented events or policies that have never been applied before leaves room for uncertainty.

While optimization models are prescriptive and econometric models rely heavily on historical data, simulation models are descriptive and focus on the identification of causal relations influencing the creation and evolution of the issues being investigated. System Dynamics models, among others, are used to inform policy making by taking into consideration elements of the context in which issues arise and by providing insights on the functioning of the system studied [28,29]. Simulation models are "what if" tools that provide information on what would happen in case a policy is implemented at a specific point in time and within a specific context. This implies identifying properties of real systems, such as feedback loops, nonlinearity and delays, via the selection and representation of causal relations existing within the system analyzed. On the other hand, the main assumptions of simulation models are the causal relations forming the structure of the model: instead of using economic theories, simulation models represent theories of how the system actually works. Practically, instead of fitting existing theories to the issues being analyzed, simulation models proposed a theory of their own, highly customized and tailored around the issues to be analyzed and the peculiarities of the system.

The validation of simulation models takes place in different stages, and two critical tests are the direct comparison of projections with historical data, which simulation models can backtrack, and the analysis of structural soundness relative to reality [30]. Potential limitations of simulation models include the correct definition of boundaries and the identification of the causal relations characterizing the functioning mechanisms of the systems being analyzed.

4. Models Review

A large number of models have been created over the years for supporting national energy planning. The use of these models, such as the Market Allocation model -MARKAL- [26,27], the framework often preferred by governments and international organizations, has provided policy makers and planners over the years with insights on policy impacts and energy technologies, in addition to offering projections on demand and supply among others. In some cases energy models (e.g., correlational ones) were also able to provide some insights on the interconnections between macro-economic development and energy management, but rarely vice-versa.

Existing models, such as in the case of the World Energy Model (WEM) [31] include a few main energy modules: final energy demand; power generation; refinery and other transformation; fossil-fuel supply; CO_2 emissions and investment. Their structure is generally a systems engineering optimization construction of the energy sector, in which engineering feasibility is ensured by making energy flows consistent with model constraints on primary-energy extraction, energy conversion and transport as well as on end-use technologies and others. These models operate under perfect foresight assumptions and optimize energy flows given demand and an objective function. This function, also called optimization routine, selects energy carriers and transformation technologies from each of the sources, to produce the least-cost solution subject to the pre- (and user) defined constraints [27].

Each model of this type slightly differs from the others in terms of details and boundaries. MESSAGE [24,25], for instance, given exogenous demand, selects the energy mix that supplies it at least cost. The WEM instead calculates energy demand econometrically, using data for the period 1971–2004 [31]. MESSAGE could only calculate demand endogenously when coupled with MACRO, a CGE model that would communicate iteratively with the energy components of MESSAGE to calculate energy prices based on the best mix of energy sources used to supply demand (e.g., demand and supply balances), which is in turn calculated using GDP too. In order to calculate demand and other macro variables in this way, economic growth and demographics have to be indicated exogenously, in addition to technology costs and technical characteristics (e.g., conversion efficiencies) [25,31].

The combination of MESSAGE and MACRO produces similar results to those of fully integrated models. The latter are market- and behavior-oriented models, where economic and energy modules are connected and rely on adaptive expectations to simulate the dynamics of the energy system (e.g., they take into account the introduction of new technology and attempt to represent their adoption process). The latest MARKAL, GEM-E3 [32], POLES [33] and PRIMES [32,34] models belong to this category. General equilibrium models (CGE) and partial equilibrium models allow for consistent comparative analysis of a policy scenario, by ensuring that in all scenarios, the economic system remains in general equilibrium.

This, though, adds important assumptions: equilibrium is assumed rather than emergent; agents perceive and respond to prices instantaneously, and may even know the future; agents have sufficient structural knowledge to respond appropriately to changes in their environment; externalities are very limited [35].

The GEM-E3 Model (General Equilibrium Model for Energy-Economy-Environment interactions) includes economic frameworks used by the World Bank (national accounts and Social Accountability Matrix) as well as projections of full Input-Output tables by country/region, employment, balance of payments, public finance and revenues, household consumption, energy use and supply, and atmospheric emissions [32]. There is no objective function in GEM-E3: being a full CGE model, the equations underlying the structure of the model define the behavior of the actors identified with the SAM [36].

The production function of the model uses capital, labor, energy and materials, and properties of the system such as stock and flow relationships, capital accumulation delays and agents' expectations are considered [32]. The main exogenous inputs to the model are population, GNP and energy intensity.

System Dynamics (SD) is employed for this study [37,38]. In T21 society, economy and environment are endogenously represented (see Table 1), requiring a relatively small number of key assumptions. T21 and other System Dynamics models, thanks to a flexible and versatile software application, are able to combine optimization and market behavior frameworks into one holistic framework that represents the causal structure of the system. SD models offer a complementary approach that allows moving toward optimal energy flows while concurrently simulating the interaction of a large number of feedback loops with the major factors in the rest of the economy, society, and the environment. This provides useful insights for policy formulation and evaluation analysis, and examples of its customization include frameworks customized to continents (e.g., North America, [5]), countries (e.g., United States [3]); Ecuador [9] and Mauritius [39]), states and regions (e.g., Lolland-Denmark- [40] and Ohio [11]). More information on the applications of T21 can be found in Bassi [3,41].

5. Proposed Approach

There has been a long-standing perception among both the general public and policy makers that the goals of economic growth, environmental protection, national and energy security involve a complex set of trade-offs, one goal against another goal [42–44]. On the other hand, when analyzing the dynamic complexity of the social, economic, and environmental systems analyzed, key feedback loops and cross-sectoral relations can be identified [3]. This leads to the understanding that all systems are somewhat interconnected and that simulation models aimed at supporting energy and climate policy should be able to account for such complexity and support the formulation of actions that might address different -interconnected- issues simultaneously (even if not at the same time, due to delays and inertia embedded in the system).

Finding that currently available energy models are either too detailed or narrowly focused and too decision-oriented and prescriptive [3], this study proposes an approach that extends and advances the energy policy analysis carried out with existing tools by accounting for the dynamic complexity embedded in the systems studied, and facilitates the investigation and understanding of feedbacks existing between energy and society, economy and the environment. This is crucial because understanding the characteristics of real systems is fundamental for the correct representation of structures whose behavior is outside their normal operating range [8]. Examples can be found in the current economic conditions, and volatility in the energy markets shows that the driving forces of today's world are rapidly changing, and have reached uncharted territories.

Table 1. Modules, Sectors and Spheres of T21-Starting Framework.

Society	Economy	Environment
Population Sector:	**Production Sector:**	**Land Sector:**
1. Population	14. Aggregate Production and Income	30. Land
2. Fertility	15. Primary Agriculture	**Water Sector:**
3. Mortality	16. Agriculture	31. Water demand
Education Sector:	17. Industry	32. Water supply
4. Primary Education	18. Services	**Energy Sector:**
5. Secondary Education	**Technology Sector:**	33. Energy demand
Health Sector:	19. Technology	34. Energy supply
6. Access to basic health care	**Households Sector:**	**Minerals Sector:**
7. HIV/AIDS	20. Households accounts	35. Fossil Fuel production
8. HIV children and orphans	**Government Sector:**	**Emissions Sector:**
9. Nutrition	21. Government revenue	36. GHG emission, CH_4, N_2O, SO_X
Infrastructure Sector:	22. Government expenditure	**Sustainability Sector:**
10. Infrastructure	23. Public investment	37. Footprint, MDG, HDI
Labor Sector:	24. Gov. balance and financing	
11. Employment	25. Government debt	
12. Labor Availability and Cost	**ROW Sector:**	
Poverty Sector:	26. International trade	
13. Income distribution	27. Balance of payments	
	Investment Sector:	
	28. Relative prices	
	29. Investment	

In order to integrate approaches and build simulation models that support policy formulation and evaluation, three levels of analysis have to be considered. These include: (1) the structure of the system analyzed (integrated, through causal relations and feedbacks), (2) possible scenarios (e.g., technological development and costs), (3) and policies (e.g., subsidies, incentives and/or mandates). How these three levels are supported by solid and coherent information, and interact with each other, will greatly determine the success of energy and environmental policies over the medium to longer term.

Firstly, in order to design and evaluate national energy and climate policies the structure of the system analyzed (e.g., social, economic and environmental) should be properly analyzed and understood. This may include the investigation of the main drivers of demand, and how supply can respond to its needs, using an optimization component integrated into a larger cross-sectoral simulation framework. This is a broad investigation relying heavily on data analysis, as we are in rapidly changing times and various social and economic sectors are strictly interrelated. High-level drivers for energy demand may include, among others, population, economic growth (e.g., GDP and income), prices and energy efficiency. Drivers of supply include the availability of primary energy sources and of secondary (e.g., electricity) generation, as well as their running and capital costs. All these factors should be endogenously represented in a long-term energy policy model.

Secondly, economic volatility, as well as natural disasters and other unexpected events can have a considerable impact on the effectiveness of energy and environmental policies over time. For these reasons scenarios -aside from the specific policies analyzed- have to be defined, to increase confidence in the analysis and correctly set the boundaries for a useful exercise. Policies will be evaluated based on the structure of the energy system analyzed as well on a variety of possible scenarios.

Thirdly, in order to test the effectiveness of various policies -and whether they create synergies or bottlenecks/side effects across sectors- for longer-term national development, provisions have to be evaluated for a variety of social, economic and environmental indicators. Policies are "shocks" to the system, which in turn responds to these changes. For this reason, the system itself should be analyzed focusing on feedbacks and causal relations, with a specific interest on medium to longer-term impacts (which go beyond the implementation delays of policies, *i.e.*, inertia of the system).

Finally, the understanding of the functioning mechanism of the system allows for the identification of medium to longer-term sectoral and cross-sectoral implications of policy implementation. These impacts have to be analyzed with the understanding that different sectors are influenced by different key causes defining the success (or failure) of policies. In other words, a policy can have very positive impacts for certain sectors and create issues for others (e.g., expanding agriculture land for food production may save the lives of many people in developing countries in the short to medium term, but if implemented at the expense of deforestation it might further exacerbate climate issues, leading to potentially much worse problems in the longer term). Furthermore, successful policies in the longer term may have negative short-term impacts, for which mitigating actions may have to be designed and implemented.

Creating a model that accounts for feedback loops, non-linearity and delays, on top of rigorously representing the energy sector, allows incorporating dynamic components of the market to the simulation tools currently utilized. Within the framework presented above, with a focus on structure, scenarios and policies, the inclusion of these characteristics of systems requires a profound customization of the model that goes beyond a new parameterization. This implies the investigation and eventually understanding of the processes that generated past changes in the behavior of the system as well as the implications of future policy implementation. Furthermore, the inclusion of social and environmental factors, in addition to economic ones, allows for a wider analysis of the implication of policies by identifying potential side effect or longer-term bottlenecks for development.

5.1. Reflections on Validation

The impossibility to identify and represent events and emergent characteristics of the system analyzed has often led to serious questions about the validity of computer simulation models aimed at generating projections. A natural conclusion of this line of thought would suggest that if factors that have profoundly changed our social, economic and environmental systems in the past, such as ruptures and discontinuities, cannot be identified or represented, the creation of forward looking scenarios may be considered a mere speculative exercise (*i.e.*, educated guesses) providing little insights. Furthermore, simulation models are mostly based on past experience and incorporate potentially biased assumptions derived through the knowledge of the researchers who created them, especially if they have not reached the "mastery" stage of learning [45]. As a consequence, since society is in continuous evolution, the creation of prescriptive models would not contribute extensively to longer-term policy analysis. Moreover, when simulation models do succeed in having a strong impact on society, they do create a new event that subsequently changes the course of things, creating the need for a further recalibration or modification of models.

Given the above, modeling complex socio-economic systems consists in a continuous improvement in knowledge of the issue analyzed and understanding of the dynamics surrounding it. The "mastery" stage of learning is effectively reached when current and past events can be properly interpreted and conceptualized [45]. A significant advantage gained in such a process resides in the fact that the knowledge and understanding accumulated strengthen the capacity to analyze the causes and consequences that future events might have on the status of the system analyzed.

Considering strengths and weaknesses of descriptive simulation models, such as T21, when coupled with other methodologies and models, the challenges mentioned above seem achievable given that:

(1) The identification of causal relations allows for the investigation of the main functioning mechanisms of the system analyzed, providing insights on the conditions that would allow future events to take place;
(2) The full understanding of the system has to do with its complexity. Simulation allows representing complexity through a descriptive, not prescriptive model;
(3) Behavioral change is continuous, while structural change can be infrequently observed. System Dynamics and systems engineering models, among others, focus on the structural representation of systems, providing insights on the motivations for behavior to change;
(4) Complexity has to be simplified to the extent reasonable to be able to understand why issues arise. Selecting boundaries is a crucial step of the modeling process, so as to take into consideration what the main factors influencing issues and behavior, in a specific time frame, may be.

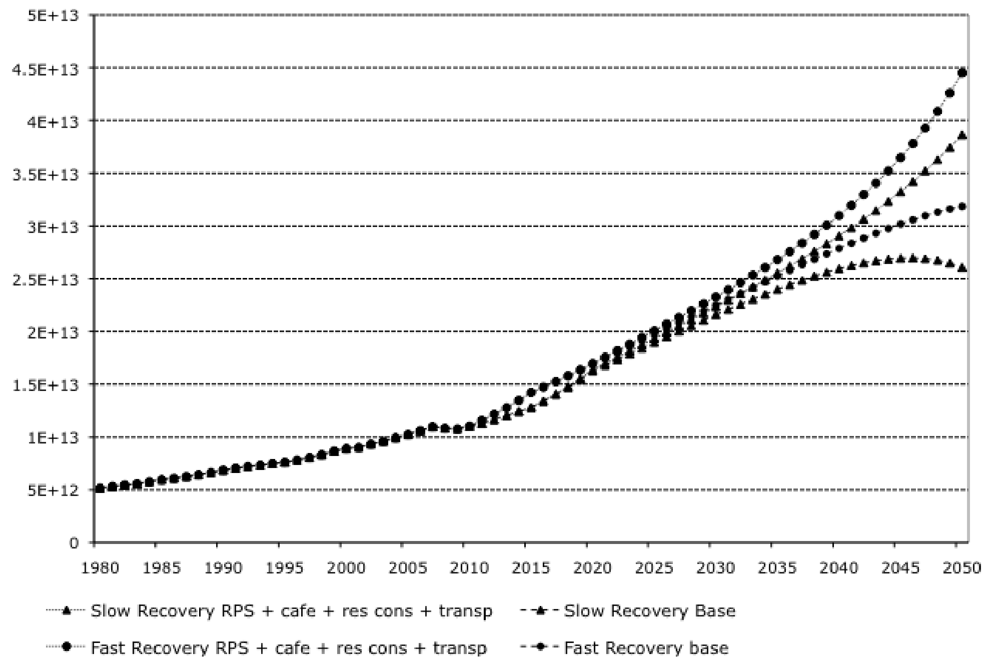
The validation of a simulation model, based on System Dynamics among others, therefore results in a gradual, semiformal and conversational process [30], where the soundness of the structure of the model is as important as the quality of the outputs of the simulation. Being "white-box" models, they provide a transparent simplified representation of reality that can be validated against real systems. This poses challenges from both a technical and philosophical angle: the former would imply that we could state with a certain degree of confidence whether a model represents reality accurately enough, and the latter relates to the unresolved philosophical issue of verifying the truth of a (scientific) statement [30]. Barlas also adds that, as a consequence, "*our conception of model validity depends on our philosophy (implicit or explicit) of how knowledge is obtained and confirmed*" [30].

6. Case Study: United Stated of America

An example of the customization of a Threshold 21 energy model, to the USA, is presented here (a detailed description of the model can be found in Bassi et al., 2009 [3] and Bassi, 2008 [45]). This analysis accounts for the simulation of a few policies, including fuel efficiency standards for passenger vehicles (CAFE), the electrification of the intercity rail system and the expansion of urban rail (TRANSP), the enactment of renewable energy standards (RPS) and energy conservation (RES CONS). In order to analyze their broader implications in uncertain economic times, two alternative economic scenarios are examined below: a quick and a slow recovery from the current economic crisis.

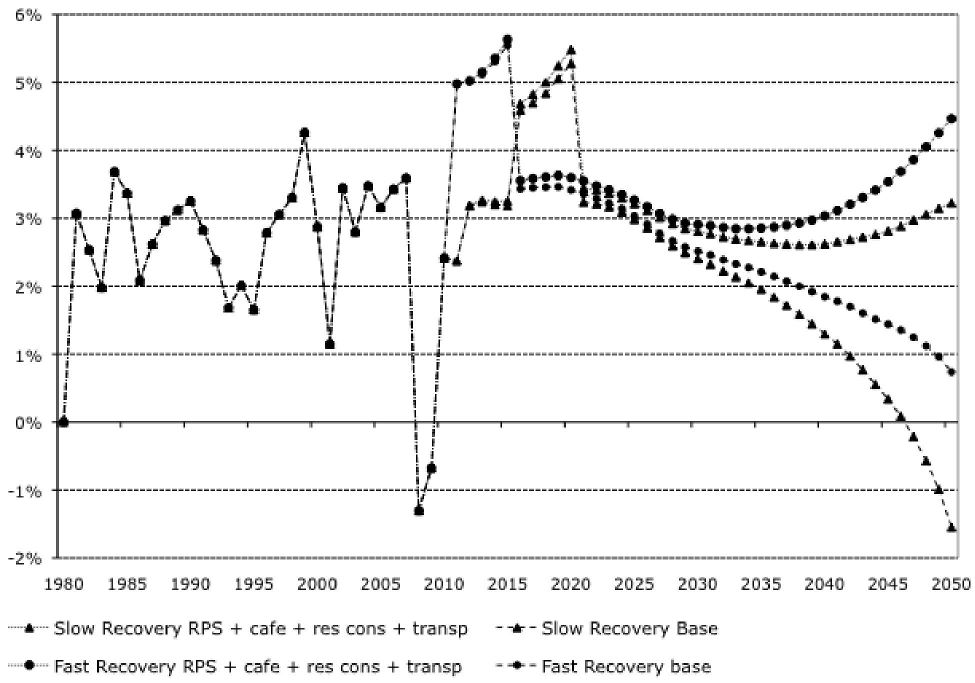
The most reasonable set of scenarios to examine is in comparison with the more rapid recovery from the current crisis base case. Without green policies, positive growth is attained in 2010, followed by several years of more rapid growth as the economy recovers much of the lost output (see Figure 2). However, GDP remains below what would have been the case in the old base run without the crisis, and the growth rate is lower over the rest of the scenario, as is per capita income (see Figure 1). Application of the green policies noted above produces higher growth rates after the recovery. Each individually produces an increase in growth, with the increased application of renewable energy sources having the more immediate and largest effects on growth, employment, and GHG emissions. By implementing all of the policies, growth rates remain around 3% pa in the 2020s and 2030s and rise to over 4% pa in the 2040s. The GDP growth with the combined policies exceeds the base case with no crisis beginning immediately following the recovery, and GDP exceeds that of the non-crisis case by 2035 (see Figure 2).

Figure 1. Results of the simulation of T21-USA, Real GDP (USD 2000/year). RPS = renewable portfolio standard; CAFE = corporate average fuel economy; RES CONS = residential energy conservation; TRANSP = electrified rail.



Total employment is also higher than the recovery base case over the whole period, with 10 million more jobs by 2050. Employment even surpasses the non-crisis case in the 2040s. GHG emissions are significantly reduced by the green policies. The combination of policies produces about 1.2 billion tons less GHG by the early 2030s than the faster recovery base case, and 1.4 billion tons less that the conventional economy without the economic crisis (see Figure 3).

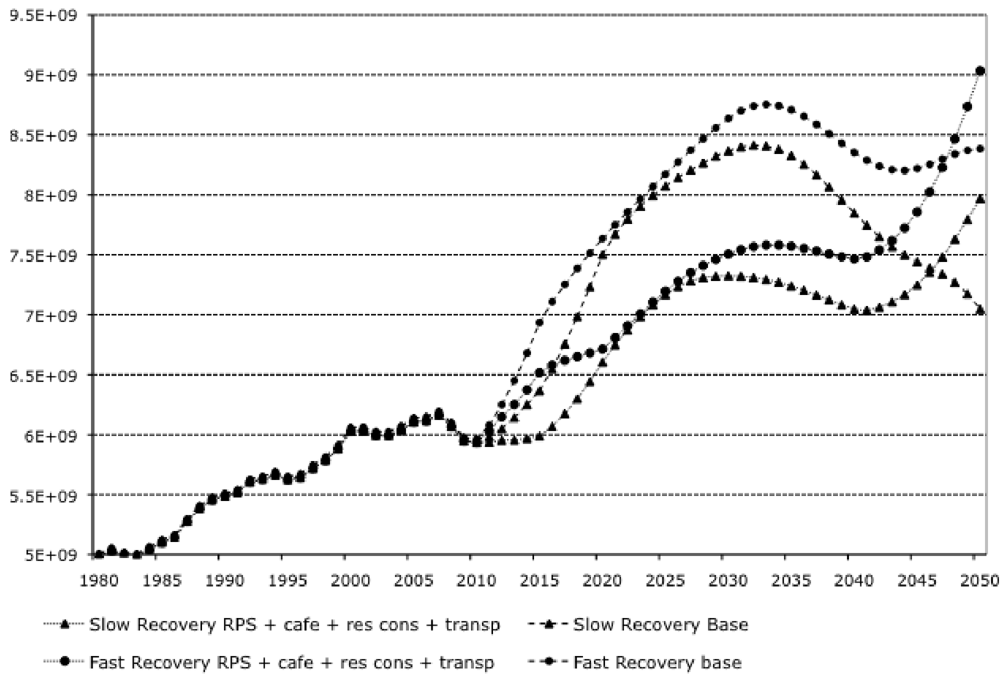
Figure 2. Results of the simulation of T21-USA, Real GDP growth rate (percentage/year). RPS = renewable portfolio standard; CAFE = corporate average fuel economy; RES CONS = residential energy conservation; TRANSP = electrified rail.



It is worth noting that the T21 USA model, with its longer term and integrated approach, also demonstrates a number of other important aspects of the implementation of these policies. The timing of their effects differs. Implementing the higher CAFE standard has a relatively slow impact. Since it applies only to newly manufactured cars, the average fuel economy of the whole auto fleet increases gradually as the older cars are retired. It takes over 15 years for the whole fleet to reach the new standards, and the impact on GHG emissions and oil demand rises slowly over time. Since it is not likely that people will buy more cars, there is not much direct impact on employment. However, as they spend less on fuel, they have more to spend on other goods, which drives up demand for domestic production over the longer term and contributes to more growth and employment. Increased renewable energy production has a more immediate impact as it creates income and jobs for the production of the additional renewable energy equipment and its installation. It has a more immediate effect on reducing GHG emissions. The residential conservation creates incremental GDP and employment as people buy more low energy light bulbs and improve insulation over the whole period, and it reduces demand for electricity, which has a positive effect on reducing GHG emissions as demand for electricity is less, and coal-fired plants are the marginal producer. The transportation electrification reduces demand for oil-based fuel as commuting and freight is shifted to rail, and it involves infrastructure construction spread over time, which helps jobs and GDP growth. Reduced transport costs also increase funds available for other consumption. However, this rail transport increases the demand for electricity, which at the margin is coal-based, so the impacts on GHG emissions are more modest.

It is also worth noting that with this combination of green policies, the GHG emission rate (total and per capita) begins to rise in the late 2040s, but stays below the scenarios without green policies. This increase is due to the higher overall growth rate of the economy, which increases the demand for energy, even though the rate of energy use and emissions per unit of GDP are lower than the base case (see Figure 3).

Figure 3. Results of the simulation of T21-USA, GHG emissions (Ton/year). RPS= renewable portfolio standard; CAFE= corporate average fuel economy; RES CONS= residential energy conservation; TRANSP= electrified rail



The effects of the green policies in the case of the slower recovery from the current crisis are similar. However, in that case, the recovery is slow and when none of these green policies are implemented, the economy is not able to sustain growth after the availability of conventional oil peaks (under the most optimistic assumptions about supplies), so GDP and per capita income begin declining in the late 2040s. This is in large part due to the impacts of accumulated debt due to the slow recovery and its negative impact on savings, consumption and investment as the burden of the debt becomes too great. Application of the green policies leads to higher growth rates. While none individually assures sustained growth, implementing them all restores sustained growth rates similar to recent normal growth of more that 3% pa. and avoids the downturn of the economy. The combination of policies creates about 20 million more jobs than the slow recovery base case by 2050, but still less than the faster recovery. GHG emissions are significantly reduced by the green policies. The combination of policies produces about 900 million tons less GHG by the early 2030s than the slow recovery base case, and 1.8 billion tons less that the conventional economy without the economic crisis.

The comparison of implementing the green policies against slower and faster recoveries emphasizes the importance of the green policies for achieving better GDP growth and job creation while reducing GHG emissions. The slower the actual recovery, the more important it is to implement as quickly as possible these green policies, and others with similar positive results that we have not yet included in the model. The model is being expanded in a number of contexts to address more green policies and over the coming year more results will be available, including the effects of imposing carbon pricing and trading on major industries, which results in significant increases in energy efficiency.

7. Conclusions

The current and the next generations are likely to face major environmental, energy and national security issues. Until now, different actions and strategic approaches were thought to be necessary to solve these interconnected issues -such as climate change, energy security and energy availability- despite the fact that they may not necessarily lead to win-win(-win) situations. This study argues instead that considering the causal relations linking these major issues, and adopting a systemic perspective, helps finding synergies across sectors.

Despite the fact that models are not, and will never be, perfect representations of reality, this research work also argues that explicitly representing the context in which energy issues arise, and where policies are formulated and implemented, enriches the analysis of energy and climate policies and provides useful insights to policy makers.

The present study proposes the utilization of an integrated cross-sectoral medium- to longer-term research approach. Key features of the method proposed include the incorporation of various methodologies in one single framework, with goals to (1) minimize key exogenous assumptions and (2) endogenously represent the key factors influencing the behavior of the system analyzed. Optimization, econometrics and simulation are analyzed, as well as the leading energy models currently being used to support policy formulation. The approach introduced is based on the explicit representation of social, economic and environmental factors in an integrated framework, so as to make the context in which energy issues arise become a fundamental driver in the modeling process and in the analysis of the results. Focusing on the structural representation of the system, potential side effects (within the energy sector and across others) were identified with a case study, thereby showing potential to effectively inform the policy debate.

Further research work is needed to better evaluate whether endogenously representing the context in which energy and climate policy would be enacted can better support the analysis carried out with simulation models. Three main areas for further work are identified: (1) methodology, where more work should be devoted to the analysis of how simulation models can be integrated with optimization and econometric models, and complement them (this would include, for instance, the evaluation of the complementarity of ABM and SD); (2) model, because the relevance of the context should be analyzed for a variety of case studies, both for detailed and broader issues; (3) dialogue, recognizing that there is a need to continue and further develop exchanges with policy makers, focusing on the understanding of assumptions and key structural relations used in models through narratives.

References and Notes

1. International Energy Agency IEA. *World Energy Outlook 2009*; OECD/IEA: Paris, France, 2009.
2. International Energy Agency IEA. *Energy Technology Perspectives (ETP) 2008*; OECD/IEA: Paris, France, 2008.
3. Bassi, A.M. An Integrated Approach to Support Energy Policy Formulation and Evaluation. PhD Dissertation, Department of Geography, University of Bergen: Bergen, Norway, 2009.
4. The factors discussed in this paper are often referred to with the acronym PESTE (political, economic, social, technologic and environmental). For simplicity, in this paper, the focus is put on

society, economy and environment, as they embed also political and technological factors. While policies are modeled and simulated, the political environment is not; and technology development and adoption are also modeled.

5. Bassi, A.M.; Schoenberg, W.; Powers, R. An Integrated Approach to Energy Prospects for North America and the Rest of the World. *Energy Economics* **2009**, *32*, 30–42.
6. Bassi, A.M. A Context-Inclusive Approach to Support Energy Policy Formulation and Evaluation. *Regional Environ. Change* **2010**, in press.
7. Sterman, J.D. A Skeptic's Guide to Computer Models. In *Managing a Nation: The Microcomputer Software Catalog*; Barney, G.O., Kreutzer, W.B., Garrett, M.J., Eds.; Westview Press: Boulder, CO, USA, 1998; pp. 209–229.
8. Sterman, J.D. *Business Dynamics: System Thinking and Modeling for a Complex World*; McGraw-Hill: New York, NY, USA, 2000.
9. Bassi, A.M.; Baer, A.E. Quantifying Cross-Sectoral Impacts of Investments in Climate Change Mitigation in Ecuador. *Energy Sustainable Dev.* **2009**, *13*, 116–123.
10. Bassi, A.M.; Shilling, J.D. Informing the US Energy Policy Debate with Threshold 21. *Technol. Forecasting Social Change* **2010**, *77*, 396–410.
11. Cimren, E.; Bassi, A.M.; Fiksel, J. T21-Ohio System Dynamics Model: Informing Waste to Profit Decisions. *Sustainability* **2010**, in press.
12. Karas, T.H. *Modelers and Policymakers: Improving the Relationship*; Sandia National Laboratories: Albuquerque, NM, USA, 2004.
13. Roberts, N.; Andersen, D.; Roberts, N.; Deal, R.; Garet, M.; Shaffer, W.D. *Introduction to Computer Simulation*; Addison-Wesley: Reading, PA, USA, 1983; p. 16.
14. Bradsher, K. *Fuel Subsidies for Some Make Oil More Expensive for All*; The International Herald Tribune: Jakarta, Indonesia, 2008.
15. Forrester, J.W. *Industrial Dynamics*; Productive Press: Portland, OR, USA, 1961.
16. Jevons, W.S. *The Coal Question*; Macmillan: London, UK, 1865
17. Dimitropoulos, J. Energy Productivity Improvements and the Rebound Effect: An Overview of the State of Knowledge. *Energy Policy* **2007**, *35*, 6354–6363.
18. Musters, A.P.A. *The Energy-Economy-Environment Interaction and the Rebound-Effect*; Netherlands Energy Research Foundation: Petten, The Netheriands, 1995. Available online: http://www.ecn.nl/docs/library/report/1994/i94053.pdf (accessed on 2 June 2010).
19. Forrester, J.W. *Road Maps: A Guide to Learning System Dynamics*; MIT Press: Cambridge, MA, USA, 2002.
20. Forrester, J.W. System Dynamics: The Next Fifty Years. *Sys. Dyn. Rev.* **2007**, DOI: 10.1002/sdr.381.
21. Hirsch, R.L.; Bezdek, R.; Wendling, R. Peaking of World Oil Production: Impacts, Mitigation and Risk Management. Available online: http://www.energybulletin.net/node/4638 (accessed on 2 June 2010).
22. Meadows, D. The Unavoidable A Priori. In *Elements of the System Dynamics Method*; Randers, J., Ed.; MIT Press: Cambridge, MA, USA, 1980; pp. 23–57.
23. Stern, N.H. Great Britain Treasury. In *The Economics of Climate Change: The Stern Review*; Cambridge University Press: Cambridge, MA, USA, 2007.

24. International Institute for Applied Systems Analysis IIASA (2001). Model MESSAGE, Command Line User Manual, Version 0.18; Available online: http://www.iiasa.ac.at/Research/ECS/docs/MESSAGE_man018.pdf (accessed on 6 March 2010).
25. International Institute for Applied Systems Analysis IIASA. *Achieving a Sustainable Energy System*; Edward Elgar Publishing: Cheltenham, UK, 2002.
26. Fishbone, L.G.; Giesen, G.; Goldstein, G.; Hymmen, H.A.; Stocks, K.J.; Vos, H.; Wilde, D.; Zöcher, R.; Balzer, C.; Abilock. H. *User's Guide for MARKAL: A Multi-period, Linear Programming Model for Energy Systems Analysis*; BNL: Upton, NY, USA, 1983.
27. Loulou, R.; Goldstein, G.; Noble, K. Documentation for the MARKAL Family of Models. Available online: http://www.etsap.org/MrklDoc-I_StdMARKAL.pdf (accessed on 8 March 2010).
28. DeGeus, A.P. Modelling to Predict or to Learn? *Eur. J. Operational Res.* **1992**, *59*, 1–5.
29. Morecroft, J.D.W. Executive Knowledge, Models and Learning. *Eur. J. Operational Res.* **1992**, *59*, 70–74.
30. Barlas, Y. Formal Aspects of Model Validity and Validation in System Dynamics. *Sys. Dyn. Rev*. **1996**, *12*, 183–210.
31. International Energy Agency IEA. Annex C: World Energy Model. In *World Energy Outlook 2004*; OECD/IEA: Paris, France. Available online: http://www.iea.org/weo/2004.asp (accessed on April 5, 2010).
32. National Technical University of Athens NTUA. *General Equilibrium Model for Economy-Energy-Environment, Model Manual*; E^3M Lab: Athens, Greece, 2006. Available online: www.e3mlab.ntua.gr/manuals/Manual_of_GEM-E3.pdf asp (accessed May 10, 2010).
33. Centre National de Recherche Scientifique CNRS Grenoble. The POLES Model: POLES State of the Art. Laboratoire d'Economie de la Production et de l'Intégration Internationale, LEPII-EPE: Grenoble, France, 2006. Available online: http://web.upmf-grenoble.fr/lepiiepe/textes/POLES12p_Jan06.pdf (accessed May 10, 2010).
34. National Technical University of Athens NTUA. *The PRIMES Energy System Model: Summary Description*; National Technical University of Athens: Athens, Greece, 2010. Available online: http://www.e3mlab.ntua.gr/manuals/PRIMsd.pdf (accessed on 10 September 2010).
35. Fiddaman, T.S. Behavioral Modeling for Science and Energy Policy. Presented at The Stanford Energy Modeling Forum EMF, Stanford, CA, USA, 2007.
36. Drud, A.; Grais, W.; Pyatt, G. Macroeconomic Modeling Based on Social Accounting Principles. *J. Policy Model*. **1986**, *8*, 111–145.
37. This study presents simulation models and focuses on System Dynamics. Agent Based Modeling (ABM), also a simulation technique, is an emerging methodology being more and more often applied to social science and resource management problems. Applications of SD and ABM are often fundamentally different in scope. Modelers using ABM aim -primarily- at investigating the relationship between agents and behavior (and very often use a bottom up approach); in our study instead -to analyze a national context, and given the nature of the policies analyzed- we adopt a top down approach. Also, ABM generates emergent results, which by definition does not allow for a full understanding of the causes driving it. This, in turn, is a strength of SD, which is fully

transparent. More information on the comparison of SD and ABM is available in Bassi and Lorenz [38].
38. Bassi, A.M.; Lorenz, T. Comprehensibility as a Discrimination Criterion for Agent-Based Modeling and System Dynamics: An Empirical Approach. In Proceedings of the 23rd International System Dynamics Conference, 17 July–21 July 2005, Boston, MA, USA.
39. Bassi, A.M. Systems Modeling of Long Term Energy Policy, Mauritius. Millennium Institute, Arlington, VA, USA, 2009. Prepared for the Ministry of Renewable Energy and Public Utilities, Republic of Mauritius, and UNDP Country Office Mauritius and Seychelles, Port Louis, August/October, 2009.
40. Magnoni, S.; Bassi, A.M. Creating Synergies from Renewable Energy Investments, a Community Success Story on Lolland, Denmark. *Energies* 2009, *2*, 1151–1169.
41. Bassi, A.M. Analyzing the Role of Integrated, Dynamic, National Development Planning Models to Support Policy Formulation and Evaluation. In Proceedings of the 3rd OECD World Forum on Statistics, Knowledge and Policy, Busan, Korea, 27 October–30 October 2009.
42. Brown, S.P.A.; Huntington, H.G. Energy Security and Climate Change Protection: Complementarity or Tradeoff? *Energy Policy* **2008**, *36*, 3510–3513.
43. CNA Corporation. National Security and the Threat of Climate Change. Available online: http://securityandclimate.cna.org/ (accessed on 10 June 2010).
44. Howarth, R.B.; Monahan, P.A. Economics, Ethics and Climate Policy: Framing the Debate. *Global Planet. Change* **1996**, *11*, 187–199.
45. Dreyfus, H. *On the Internet: Thinking in Action*; Routledge Press: London, UK; New York, NY, USA, 2001.