An Integrated Approach to Support Energy Policy Formulation and Evaluation

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Dissertation for the degree philosophiae doctor (PhD)

at the University of Bergen

November 27, 2009

Scientific environment

This thesis uses the System Dynamics methodology to support and analyze energy policy formulation and evaluation.

This research was carried out with the collaboration of the Millennium Institute and the System Dynamics Group, University of Bergen, under the supervision of Prof. Pål I. Davidsen.

Acknowledgements

My research has been influenced by various collaborators and friends. I wish to thank them for their support and thoughtful advice.

Firstly, I would like to express my gratitude to Prof. Pål I. Davidsen, my thesis supervisor, for his precious advice and guidance throughout the years. This research would have not been possible without Pål's support. Along with Pål, I wish to thank the System Dynamics Group at the University of Bergen, a constant source of knowledge and a solid group of friends.

Further, my appreciation goes to Dr. Hans R. Herren, President of the Millennium Institute (MI). Hans' support for my research has always been strong and felt, and I deeply appreciate it. Many thanks also to Dr. Matteo Pedercini, which introduced me to MI and with whom I have shared many unforgettable experiences over the last few years.

Many thanks also to the co-authors of the work on the proposed studies, with which over time I have developed a friendship and have experienced many life enriching events. Dr. Allan Baer introduced me to the fascinating energy efficiency projects of the Galapagos Islands and Ecuador, and offered me the opportunity to spend some very enjoyable time at Middlebury College in freezing Vermont; William Schoenberg (Billy) and Robert Powers (Bobby), which I had the pleasure to introduce to System Dynamics, supported the intense work on the North America study, together with ASPO-USA in upstate New York; Dr. John (Jed) Shilling, also Chairman of the Board of the Millennium Institute, a daily source of good advice and knowledge, provided key indications on how to develop the USA analysis; Alan Drake, a visionary mind from New Orleans, always ready to help and support others for good causes, was an incredible source of inspiration for the transportation case study; Dr. Joel Yudken, a system thinker fully committed to support policy formulation with rigorous methods and analysis, has been a key collaborator in making the energy intensive industries case study a success.

Over time, I have also had the pleasure to encounter exceptional personalities that have strongly motivated me to always do my best in every situation, especially on research and this thesis. I will certainly treasure many of the conversations I had with Hemang, Sanju and Donatella.

Finally, a heartfelt thank you goes to my family and Silvia, my future wife. None of this would have been possible without your moral support. This thesis is dedicated to you, always close to me, no matter how far we are from each other.

Abstract

With the adoption of the Kyoto Protocol (UN, 1997) in 1997 and the recent increase in energy prices, national leaders of industrialized countries have started investigating options for reducing energy consumption and carbon emissions within national borders (UNFCCC, 2008). After ten years debating on whether the global and national economies would have been negatively impacted by the implementation of such measures, rising global concerns on climate change urge policy makers to find ways to reduce the carbon intensity of the global economy (IPCC, 2007).

Various proposals for reducing energy consumption and supply cleaner fuels have been examined during the years. Some countries opposed the adoption of drastic measures -such as the US, which has not yet ratified the Kyoto protocol, while others have taken the lead to support the diffusion of energy efficient technology and promote the production of cleaner energy, such as Denmark and Germany. As a matter of fact, different governments find themselves in different energy contexts that direct them towards taking dissimilar positions on energy issues. Evidently, the extent to which society, economy and environment shape policies and react to their implementation change from country to country.

The present study investigates whether contextualizing energy issues is relevant to provide support to energy policy formulation and evaluation aimed at finding sustainable longer-term solutions to today's and upcoming energy and environmental issues. Instead of applying the most widely accepted tools used to support policy formulation and evaluation, this research proposes the utilization of a holistic framework that incorporates social, economic and environmental factors as well as their relations to the energy sector, to better contextualize global, regional and national energy issues. This framework, which accounts for feedback

loops, delays and non-linearity, is applied to case studies centered on the US to investigate the longer term performance of selected energy policies under a variety of scenarios.

Results of the research work carried out with five case studies, focused on the simulation of various energy and climate policy options, indicate the likely emergence of various unexpected side effects and elements of policy resistance over the medium and longer term, due to the interrelations existing between energy and society, economy and environment. Furthermore, side effects or unintended consequences may arise both within the energy sector and in the other spheres of the model; nevertheless, these behavioral changes influence all society, economy and environment spheres.

List of publications

Bassi, A.M., A. E. Baer, "Quantifying Cross-Sectoral Impacts of Investments in Climate Change Mitigation in Ecuador". Energy for Sustainable Development 13(2009)116-123, doi:10.1016/j.esd.2009.05.003

Bassi, A.M., Schoenberg, W., Powers, R., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics, In Press, doi:10.1016/j.eneco.2009.04.005

Bassi, A.M., and J.D. Shilling, "Informing the US Energy Policy Debate with Threshold 21". Technological Forecasting & Social Change, In Press.

Bassi, A.M., A. Drake, E.L. Tennyson and H.R. Herren, "Evaluating the Creation of a Parallel Non-Oil Transportation System in an Oil Constrained Future". Submitted to Transport Policy and peer reviewed by -and presented at- 2009 TRB Conference: Annual Conference of the Transportation Research Board of the National Academies of Science, Engineering, and Medicine, January 11-15, 2009, Washington DC, USA.

Bassi, A.M., Yudken, J.S., Ruth, M., Climate policy impacts on the competitiveness of energy-intensive manufacturing sectors, Energy Policy 37(2009)3052–3060, http://dx.doi.org/10.1016/j.enpol.2009.03.055

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1. Introduction

1.1 Energy Trends and Issues

The current and the next generations are likely to face major environmental, energy and national security issues. According to the International Energy Agency (IEA) important changes are expected to take place within the energy sector in the upcoming decades with global primary energy demand projected to increase by more than 50% by 2030, at an average annual growth rate of 1.6% (IEA, 2006). As reported in the World Energy Outlook (WEO) published in 2006, global energy demand will shift to new areas, mainly driven by today's emerging countries such as China and India and with developing countries' rising population and accelerating economic growth rates (IEA, 2006) being responsible for over 70% of the projected increase in energy demand. This consideration relates to the fact that developing countries have shown a greater need for electricity and motorized transport, which to date are still less developed than in industrialized countries. Consequently, nearly one half of the increase in global primary energy use goes to generating electricity and one fifth to meet transportation needs, almost entirely for oil-based fuel, in developing states.

According to IEA fossil fuels demand is therefore projected to increase significantly and account for 83% of the overall increase in energy demand between 2004 and 2030. World oil demand, 84 mb/day in 2005, should reach 99 mb/day in 2015 and 116 mb/day in 2030. Coal is expected to remain the cheapest and therefore fastest growing energy source over the period considered, due to an ever-increasing power generation especially in developing countries. Natural gas demand grows as well despite increasing prices.

IEA projections of carbon-dioxide (CO_2) emissions indicate an increase by 55% between 2004 and 2030 due to increasing energy consumption, thereby reaching 40 gigatonnes (Gt) in 2030 and growing at an annual rate of 1.7%. Power

generation, which uses large amounts of coal, should represent 50% of the increase mentioned above. These developments, if materialized, could lead to a series of major interconnected problems: climate change, national security and energy security. The CO_2 concentration correspondent to the projections above will be between 500 and 600 ppm, the average atmospheric temperature will increase by 3.34°C (IEA, 2008) and relevant climatic consequences may occur, such as extreme weather events, drought, flooding, sea level rise, retreating glaciers, habitat shifts, and the increased spread of life-threatening diseases (IPCC, 2007).
If such a scenario materializes, the world might have to face geo-political instability, fomenting conflicts among net energy exporters and importing countries, in addition to the damages generated by increasing generation of fossil fuels emissions. Projected climate change poses therefore a serious threat to national security (CNA, 2007; G. W. Bush, 2007) as its foreseen impacts have the potential to radically modify "our way of life and to force changes in the way we keep ourselves safe and secure" (CNA, 2007). The Center for Naval Analysis (CNA) also identifies climate change as a threat multiplier for instability in some of the most volatile regions of the world, which are the ones disposing of large stocks of fossil fuels, thereby generating a positive feedback in terms of risks associated to it. UNDP specifies that currently there is no problem in terms of the availability of energy resources worldwide to meet energy demand for the foreseeable future. However, whether these resources will be available in the marketplace at affordable prices depends, aside from external events, on how markets perform, government taxation and regulation and role of policies such as electrification or subsidies (UNDP, 2004).

According to the National Petroleum Council (NPC, 2007) climate change and energy security threats will eventually trigger energy security issues related to reliable supply, affordable energy, political hurdles, infrastructure requirements (especially in developing countries), and availability of trained work force able to move freely where needed (NPC, 2007).

Although the IEA projections do not provide an analysis of various scenarios concerning world crude oil production, the peaking of world oil production is an element of uncertainty that requires particular attention due to its potential implication for policy formulation and implementation (Brecha, 2008). The World has been lately experiencing a situation in which increasing demand for oil is not readily matched by supply (which has been about constant over the last 4 years (EIA, 2007)), which, together with other factors, have driven oil prices to increase 5 fold in the last 5 years (EIA, 2007). Compared to the oil crisis in the late seventies it has to be noted that today's situation is fundamentally different (both for the energy sector and global economy) (GAO, 2007). The above-mentioned energy, environmental and national security challenges therefore force policy makers to look into uncharted territories to find possible solutions. Unfortunately, as Hirsch Report concludes, there is a need to identify and implement the best solutions soon: "*Viable mitigation options* (to reduce the impact of peaking world oil production (Hubbert, 1956)) *exist on both the supply and demand sides, but to have substantial impact, they must be initiated more than a decade in advance of peaking*" (Hirsch, 2005).

In industrialized countries, in addition to rigid and stratified market structures, demand is becoming increasingly insensitive to prices, leaving little room for painless and effective transitions to a more open and deregulated market (IEA, 2006). The Energy Information Administration (EIA) of the US Department of Energy (DOE) reports that as a result of rising oil and gas demand during years of tight energy supply, energy demand has become increasingly insensitive to energy price especially in the transportation sector, which is heavily relying on liquid fuels (EIA, 2007). This insensitivity increases the vulnerability of importing countries to peak oil, supply disruption and price shocks. Furthermore, as both demand and depletion increase, a growing number of countries must rely on imports coming mainly form the Middle East and along vulnerable maritime routes. If, on top of the above we add that the IEA projects non-OPEC production of conventional crude oil and natural gas liquids to peak within a decade, the outlook on energy security does not look promising.

Unsurprisingly, the effects of sustained high energy prices on the global economy are complex and uncertain. While high energy prices have meant higher costs for industries and households (most oil-importing economies around the world would have grown more rapidly from 2002 had the price of oil not increased), exporting countries have reported all time high revenues. A further complication stems from the fact that the price of non-energy commodities has also increased lately, overweighting the impact of higher energy costs on importing countries, which have consequently experienced a worsening of their current account balances. The overall IEA assessment on energy security is as follows: "*The longer prices remain at current levels or the more they rise, the greater the threat to economic growth in importing countries. An oil-price shock caused by a sudden and severe supply disruption would be particularly damaging—for heavily indebted poor countries most of all.*" (IEA, 2006)

Climate change, national security, and energy availability can therefore be considered a related set of global challenges (CNA, 2007). Energy consumption generates emissions, whose accumulation strengthens global warming, which in turn creates instability and may lead countries to fail. This generates issues in energy distribution, pricing and accessibility, aside from problems that may emerge due to oil depletion and scarcity. It is not difficult to foresee that countries heavily relying on oil may suffer from the worsening of what is already a fragile political stability. The United States for instance, with only 2 percent of the world's proven oil reserves but 26 percent of the world's consumption, will still be heavily relying on imported energy as the Nation is not in the position to easily solve energy and environmental issues by increasing domestic production (UCS, 2002).

In the framework of the above outlook on energy prospects, the IEA identifies two main problems for today's society (IEA, 2006):

1. The lack of adequate and secure supplies of energy at affordable prices, which underlies problems in reducing fossil fuel energy demand and increasing geographic and fuel-supply diversity (i.e. national security);
2. The environmental problems caused by global warming and by ever increasing energy consumption.

On the other hand the World Energy Assessment (WEA), published by the United Nations Development Program (UNDP), reporting on the impact of the evolving energy sector on the status of developing countries, identifies the following as the main energy-related challenges for the years to come (UNDP, 2004):

a) Reducing dependence on imported fuels to limit a country's vulnerability to disruption in supply.
b) Increasing access to affordable energy services. In fact, it is access to energy services not energy supply that matters considering the troubled geographical distribution of supply.
c) Promoting access to decentralized small-scale energy technologies as an important element of energy sustainability at the community level.
d) Mitigating the environmental impacts of energy-linked emissions that contribute to local and regional air pollution and ecosystem degradation.

According to UNDP, finding ways to expand energy availability and accessibility while simultaneously addressing the environmental impacts associated with energy use represents a critical challenge to humanity. In accordance with the indications provided by the IEA, UNDP confirms that major changes are required in energy system development worldwide.

Considering the causal relations linking climate change, energy security and energy availability different actions and strategic approaches should be taken to solve these interconnected issues, and they may not necessarily lead to win-win (-win) situations. As noted by Brown and Huntington, policy makers may give priority to energy security, leading to the adoption of conventional and readily available technologies, while climate change would require investments in more energy efficient, and costly, technologies that would yield benefits in both increasing energy security and reducing emissions (Brown and Huntington, 2008). In recognition of such interrelations between climate change, energy availability and national security, CNA (CNA, 2007) and Lengyel (Lengyel, 2007) suggest that these three issues should be fully integrated into national security and national defense strategies. In addition, they call for industrialized countries to commit to a stronger national and international role to help stabilize climate change at levels that will avoid significant disruption to global security and stability.
A range of policies can be implemented to improve energy security. In this respect, one effective strategy would target reduced dependence on fossil fuel imports. This strategy encompasses policies aimed at diversifying supply – both geographically and among various primary energy sources – as well as increasing end-use efficiency and encouraging greater reliance on local energy production, including renewable resources. Promoting renewable energy carries along other positive externalities such as job creation and pollution reduction, provided that these do not have disproportionate costs or use a large portion of already scarce resources. It has to be noted though that while the investment in renewable energy is advised by UNDP and is well received in developing countries (AusAID, 2000; REN21 and Worldwatch Institute, 2005), with the aim to increase the decentralization of energy distribution and reduce the vulnerability of supply lines, such structural change in the power sector is not equally well received by utilities

and lobby groups in the United States and other developed and industrialized countries (EIA, 1998; Kydes, 2006).

The WEO 2006 analyzes several scenarios using the IEA World Energy Model (WEM) (IEA, 2004) to identify what such changes should be. While the reference scenario indicates that, in the absence of new government action, energy demand and subsequently greenhouse-gas emissions would follow their current unsustainable paths through to 2030, an Alternative Scenario shows that the increase in energy demand and consumption can be significantly reduced when a number of policies are implemented at the national and regional level. Interestingly, the WEO shows that "*the economic cost of these policies would be more than outweighed by the economic benefits that would come from using and producing energy more efficientl*y" (IEA, 2006).

In the Alternative Scenario, various policies and measures aimed at enhancing energy security and mitigating CO_2 emissions are assumed to be implemented. These include efforts to improve energy efficiency (in both production and use), increase renewable energy production, and sustain the domestic supply of oil and gas within net energy-importing countries. While various governments all over the world are considering the implementation of such policies, according to IEA: "*It will take considerable political will to push these policies through, many of which are bound to encounter resistance from some industry and consumer interests.*" Though the results of the Alternative Scenario are encouraging, the IEA states "*... each year of delay in implementing the policies analyzed would have a disproportionately larger effect on emissions*" (IEA, 2006). Such statements make reference to two significant aspects, the relevance of the political context and the role of feedbacks, that are not being addressed with WEM (IEA, 2004), but that are of utmost importance when dealing with complex and interconnected issues.

To conclude, many reports, including WEO (IEA, 2006) and WEA (UNDP, 2004), suggest that that three of the most important challenges human kind had ever faced are emerging: climate change, national security and energy security. These challenges are obviously related and require a large and timely effort from both developing and industrialized countries, with the latter being in the driver seat due to their high energy consumption and rich economies.

The reports released by the IEA and UNDP among others indicate that modern society has to deal with complex interconnected systems characterized by properties that may be misperceived, such as feedbacks, non-linearity and delays, where energy influences the economy as well as the quality of life and well being of populations.

To reach down to energy consumption levels that would allow us to reduce emissions to sustainable CO_2 concentration in such a dynamic and complex system, there is a need to define vision, goals and strategies (i.e. policies). In addition, such vision has to be transferred to key actors in the economy, including households, by providing continuous support and policy certainty going forward (RFF, 2007). Finally, policies have to be monitored and eventually adjusted to evolve over time, together with the changing environment.

The present research work argues that, even though existing studies propose the simulation of a variety of policies in different areas, they do not consider (i.e. incorporate in the models used) the social, economic and environmental dimensions (e.g. importers vs. exporters, developed vs. developing countries) that characterize individual countries and lead them to respond differently to the similar energy issues. Such a reaction can be identified in the fact that society, economy and environment may evolve following different paths according to their unique structures and in response to the decisions of the actors involved. In addition, scenarios on "externalities" seem to be missing in the work of the leading national and international organizations supporting policy making in the energy sector. World oil production scenarios, among others, have to be taken into account to provide a full overview of what the impact of the upcoming energy transition may be, what levels of emissions will be generated and what the likely consequences of climate change could have on society, economy and the environment. Brecha states in fact that even with an early decline in world conventional oil production, CO_2 concentration could still be higher than 550ppm in 2050 (Brecha, 2008), so this remains an actual problem that should be investigated to reduce the risk associated with it and plan mitigation and adaptation strategies. Conducting scenario building exercises, coupled with the simulation of an integrated quantitative model to test policy options would allow for the preparation of early action plans. As stated in the Hirsch report, acting before irreversible changes in oil supply take place is the best strategy to avoid negative feedback loops gaining strength and have larger impacts on fuel prices as well as economic, social and environmental mitigation costs (Hirsch, 2005).

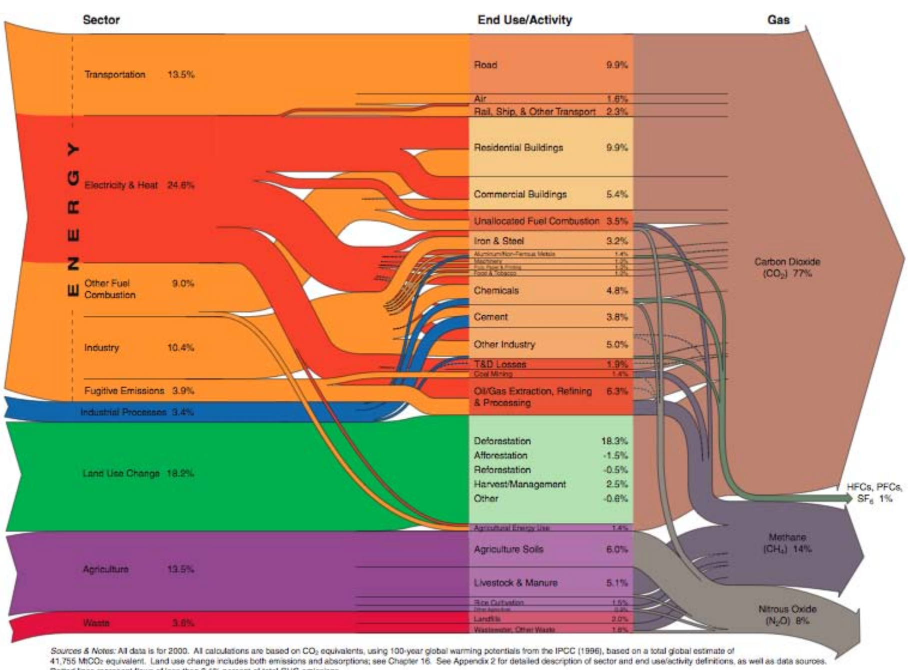
The following section provides an introduction to renewable energy policies designed and implemented by different countries, United States in primis. Such an introduction aims at highlighting what characteristics and events allowed certain policies to be successful in some cases and less encouraging in others.

1.2 Challenges to Policy Formulation and Implementation: Renewable Energy

A number of policies are currently being promoted to reduce energy consumption and emissions and increase energy security. In the United States, for instance, the most common recommendations include increasing energy efficiency, expanding while diversifying supply, strengthening global energy trade, investing in engineering and developing a framework for carbon capture and sequestration (NPC, 2007). Such recommendations emerge from concerns related to the need to increase reliable and secure supply while curbing demand growth and generating jobs and opportunities for the upcoming new and needed generation of skilled workforce in the energy sector.

In the framework of worldwide interventions, although it did receive criticism due to the higher cost for electricity generation (EIA, 1998; Global Energy Services, 2005; Scott, 1997; Standard & Poor, 1998; CEI, 2007), the expansion of renewable energy production is indicated as one of the actions that can contribute to strong future economic growth, increase in energy security through the creation of decentralized power distribution and reduction in fossil fuels-related harmful emissions. In addition, the power sector is largely contributing to the generation of CO_2 and GHG emissions, as shown in the flow diagram below (World Resources Institute, 2005).

Figure 1: World GHG emissions flow chart, 2000.



Starting from the energy crises of the 1970s, investments in renewable energy have increased in many countries. Those countries that saw renewable energy as a way to reduce oil imports have generally reduced their effort to increase the penetration of renewable energy after 1984, when oil prices returned to the level of the late seventies. Other countries, perceiving this investment as a strategic component of their national plans, have continued promoting renewable energy to protect the environment and stimulate the economy by creating a new domestic industry. These countries used strategies that are still being discussed, such as removing subsidies to conventional energy supply and applying tax credits to green energy (see Hassett and Metcalf, 2007).

The above partly explains why, though there has been a general agreement on the advantages provided by the adoption of renewable energy on a large scale, various countries have followed different paths over the years and are now at different levels of renewable energy penetration in domestic electricity generation. Germany, Denmark, the Netherlands, Japan, the U.K. and the US have followed different paths and applied different policies between 1970 and 2003, as highlighted by the Energy Information Administration (EIA) (EIA, 2005) and by J. Lipp (Lipp, 2007). These two studies analyzed policy design and implementation ex-post, by monitoring the actual effectiveness of policies in increasing non-hydro renewable generation and energy security, and in reducing CO_2 emissions. For this reason the approach used does not allow for the analysis of policies currently being discussed (or recently implemented), due to the lack of measurable outcomes. On the other hand, the authors provide insights on critical success factors in renewable energy formulation and implementation that can still be very useful to other countries.

There are many differences between the countries analyzed in the EIA study, as well as in regions forming them. These include natural resource endowments, political and economic systems, and cultural traditions. All of these factors can lead to differences in energy costs and prices as well as influence the effectiveness of policies. Firstly, natural resource endowments are given and are relevant because they are the basis on which the energy portfolio of countries is defined

(IEA, 2004). Secondly, the unique social, economic, environmental and political contexts characterizing each country affect policy formulation (and choices) and may even make some policies not applicable in certain countries. In other words, as J. Lipp states, "*Although most countries share these objectives, their choice of policy varies, explained largely by national context*" (Lipp, 2007). In addition to that, further valorizing the importance of the context, all the analyzed countries have considered only two main mechanisms for increasing the penetration of renewable energy: the Feed-In Tariff (FIT)[1] (WFC, 2007) and the Renewable Portfolio Standard (RPS)[2] (WRI, 2007).

The results of the EIA and Lipp's studies show that the implementation of policies to increase the penetration of non-hydro renewable electricity was more successful in Denmark, Germany, U.K. and Japan, than in the Netherlands and the United States. While the explanation of such diverse developments, in a technical and optimization-type analysis (DOE, 2008; EIA, 2007), would be linked to the natural endowment of renewable resources at the national level, Lipp identifies two additional main factors, (1) policy design and (2) government commitment (Lipp, 2007), which are further supplemented by EIA's four key factors: (3) political and economic systems, (4) cultural traditions, (5) electricity prices and (6) public opposition (EIA, 2005).

Generally, policy makers in Germany, Denmark, U.K. and Japan proposed and implemented coordinated and consistent policies that have in fact helped the development of the non-hydro renewable energy sector, which has been considered as a strategic investment opportunity, and has supported the growth of

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[1] Feed-in Tariffs legally oblige utility companies to buy electricity from renewable energy producers at a premium rate. Renewable energy installations are interconnected with the electricity grid, and the premium rate is designed to generate a reasonable profit for investors over the longer term (20 years in Germany). This makes the installation of renewable energy systems a secure investment and the extra cost is shared among all energy users. World Future Council, Feed-In Tariffs: Boosting Energy for our Future, 2007.

[2] A RPS requires that a minimum percentage or amount of electric power generation come from eligible renewable energy sources by a specified date. Retail electric power suppliers (also known as load-serving entities) must purchase power directly from renewable electricity generators. WRI Issue Brief National Renewable Electricity Standard, 2007.
Design Features: http://pdf.wri.org/national_renewable_electricity_standard_design_features.pdf

a new industry, the creation of jobs and reduction of emissions. A very high political commitment has in fact accompanied the Danish, German, British and Japanese successes in developing their renewable energy sector. One example for all, in Denmark the goals set by the government in 1981 (production of 1.3 billion kWh of electricity from renewables by 1995), was met by 1993 thanks to the allocation of subsidies for the production of electricity from wind turbines. A second goal was set in 1990 (for the installation of 1,500 MW of capacity by 2005), and this goal was met in 1998 thanks to generation subsidies and guaranteed pricing policies (Sawin, 2001; IEA, 2003). Finally, the last goal was set in 1991 as part of the Energy 21 policy, a goal of 5,500 MW of renewable capacity by 2030. Meanwhile, Denmark has become a net exporter of energy as of 1998, has a penetration of renewable energy close to 20% and has been well on the way to reach that goal ahead of schedule.

The continuous commitment expressed by the Danish Government is in contrast with evidence in the United States, where the Government, especially the Republican Party, has been reluctant in accepting Renewable Energy Standards and in extending renewable energy tax credits expiring at the end of 2008. In this case longer-term vision and strategy seem to be missing, undermining the allocation of investments in the renewable energy sector (WRI, 2005) and generating fear of a boom and bust cycle in the US renewable energy sector (UCS, 2005).

Further, in the United States a divergence, and at times inconsistency, between Federal and State policy has prevented actions aimed at increasing renewable energy penetration to be successful. In this respect, the International Energy Agency finds missing cohesion at the federal and state level in the design of energy, environmental and security policies (IEA, 2007). Despite the availability of a variety of individual policies and propositions, most of them have a narrow focus and address aspects of energy, environment and energy security that do not

suit, or are not applicable to all states (e.g. federal RPS propositions, see US Chamber of Commerce, 2007). As a result, such policies are not consistent and coordinated when looking at the energy sector as a whole as well as at its connections with society, economy and environment. According to the IEA "*This lack of a balanced policy is contributing to the continued high and growing dependence on fossil fuels, a situation that is almost unique among IEA member countries, which in turn contributes to increasing import dependence, and worsening the environmental impacts of energy use*" (IEA, 2007). On the other hand, recent studies are showing that the growing number of initiatives being taken at the state, regional and local level, especially in areas that are not applicable at the federal level, despite the delay due to policy negotiations, will be leading to considerable reductions in CO_2 emissions in the United States with respect to business as usual projections (Lutsey, Sperling, 2007).
In the United States, a closer look at the requirements of society, economic development and environmental preservation, would be needed to propose a more balanced and effective energy policy that would bring cohesion to the system. This is confirmed by IEA and Government Accountability Office (GAO) (GAO, 2007) studies. According to the IEA decentralized policy formulation at the state level has serious consequences on both the costs and effectiveness of implementing such policies (IEA, 2007). Creating policy cohesion is very difficult when there is little coherence among the institutions responsible for policy formulation and implementation. Policies are proposed both at the federal and state level, but they seem to be "*disjointed in terms of pace, consistency, continuity, and approach*" (IEA, 2007). According to a study carried out at the Lawrence Berkeley National Laboratory, tools for supporting policy making at the State level are not able to provide consistence guidance on State policies, making it more difficult to coordinate activities with the Federal Government (Chen, Wiser, and Bolinger, 2007).

This is unfortunate since there are various ways in which State and Federal

Governments can cooperate to design and implement effective policies. The World Resources Institute summarizes the two most common ones as follows: (1) when states lead in policy development, they usually propose innovations that can influence federal action; (2) when the policy debate regards national issues or concerns, the federal government provides political guidance and leadership that states do not always possess (WRI, 2007).
According to GAO, policy makers and resource managers often focus on near-term activities leaving too little time for addressing longer-term issues such as climate change. Furthermore, GAO identifies a lack of tools and simulation models for more detailed and integrated analysis, which limits the actions of policy makers to already-observed climate change issues, which results in very limited and ineffective longer term planning (GAO, 2007).

Again, both GAO (GAO, 2006) and IEA are concerned that the policies currently being discussed will not lead the United States to reduce oil dependency and greatly increase renewable energy penetration in the years to come. A strong political commitment from the federal government and a more integrated analysis of the interdependencies existing among energy, society, economy and the environment, would certainly improve policy efficacy in the U.S.

1.3 Study Purpose and Overview

The purpose of this study is to contextualize energy issues to evaluate whether their comprehensive representation into an integrated simulation model effectively supports policy formulation and evaluation. Recognizing that currently available energy models are either too detailed or narrowly focused and too decision oriented and prescriptive, 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. Understanding the characteristics of real systems is fundamental for the correct representation of structures whose behavior is outside their normal operating range. Current economic conditions and volatility in the energy markets show that the driving forces of today's world are rapidly changing, and have reached uncharted territories. For this reason, most researchers using models and methodologies that performed well in the past 30 years, during a time of steady economic growth and stable international markets, are now struggling to address key energy issues, being unable to account for potential longer term policy-induced side effects and unexpected consequences caused by rapidly changing market drivers, which are governed by feedback (both internal and cross-sectoral), delays and nonlinearity (e.g. accounting for disproportionate reaction of similar events and decisions). These three characteristics of real systems are key to the methodology utilized in this study, and help defining the context in which issues arise, and when applied to energy issues, which are very much interconnected with society, economy and environment, allow for a more coherent representation of their context.

The present study is organized in a series of sections. The *Research Motivation* introduces the performed research work, which proceeds with an explanation of the *Research Approach* used. Such an approach is then applied to customize the models used to carry out the analysis, which are presented and described in the *Research Tools and Analysis* section. The *Main Findings* of each case study are introduced next and a presentation of the insights gathered from the customization of Millennium Institute's[3] Threshold 21 (T21) (Millennium Institute, 2005) and

[3] The Millennium Institute (MI) is a not-for-profit development research and service organization headquartered in Arlington, Virginia, USA. Founded in 1983 by Dr. Gerald O. Barney as follow up to the Global 2000 Report to the President, MI is committed to finding practical means to promote sustainable development. MI's mission is (1) to develop and provide advanced analytical tools for national and global development; and (2) to formulate values-related questions and analyses on the consequences of alternative development strategies. www.millennium-institute.org

the Minimum Country Model (MCM) (Pedercini et al., 2008) precedes the *Conclusions* of the research work.
The specific case studies are presented as separate papers and the appendixes include a study on the performance of previous T21 applications carried out by the Millennium Institute, a comparison of the results of the models customized for this study with those developed by the EIA and IEA, and finally the models documentation.

To begin with, the motivations for this research are presented in Section 2. These include the necessity to find solutions to the upcoming energy issues as well as the need to support policy makers with the understanding of such issues, and the systems in which they arise, with tools that allow for the representation of the context in which decisions have to be made and implemented. Policy decisions are dependent on the social, economic, environmental and political contexts and require modelers to establish a relationship with policy makers and stakeholders based on mutual trust, on top of creating a valuable tool, in order to be successful and work effectively to support policy formulation and evaluation.

In Section 3 the research approach, which is focused on identifying the context in which energy issues are embedded, is analyzed more in details. The *Research Approach* section provides an introduction to the method used to analyze energy issues from a global, regional and national perspective. The research steps are presented, as well as the main guidelines applied when communicating with policy makers, experts and stakeholders.
A geo-political presentation of selected issues accompanied by a description of the main properties of complex energy contexts (i.e. feedbacks, delays and nonlinearity) follows.
Finally, a review of the main methodologies and models that are currently being used to support policy formulation and evaluation is proposed to verify whether

they encompass the context around energy issues and are able to provide insightful results to policy makers.

Section 4, *Research Tools and Analysis*, introduces the methodology and models used to carry out the research hereby presented: System Dynamics (SD)-based models. Firstly, the foundations and applications of the methodology are investigated to determine whether SD can provide value added with respect to econometrics and optimization techniques when aiming at understanding systems complex and uncertain. Secondly, the models adopted in this study are presented. These include the starting frameworks of the Threshold 21 (T21) and Minimum Country Model (MCM) developed by the Millennium Institute, as well as the customized versions of such models to represent Ecuador, North America, the United States and the more detailed U.S. transportation and energy intensive manufacturing sectors.

After the brief introduction to the models, in Section 4 their use is described in terms of what policies and scenarios are simulated. The *Research Analysis* section highlights what relevant policy instruments are being considered and developed at the national level to reduce fossil fuel consumption and curb GHG emissions growth, as well as what uncertain parameters were simulated to cover a large range of future possible developments.

A presentation of the background and main findings of the five case studies is proposed in Section 5. The Ecuador study (1) analyzes the results of a global study, the Stern Review on the Economics of Climate Change (Stern, 2007), and the insights it provides to national policy making. The North America study (2) investigates the impacts of the peaking of world oil production on society, economy and environment at the national level and on trade for the NAFTA region (Canada, United States and Mexico). The US national analysis (3) aims at evaluating the wider impacts of energy policies currently being discussed, such as

RPS and CAFE standards. The more detailed analysis of the US transportation sector (4) and energy intensive industries (5) concentrates, respectively, on evaluating the use of mature technology to move towards environmental, energy and national security goals, and on the analysis of countrywide cap-and-trade proposals.

1. The Ecuador analysis indicates that, even though investing 1% of GDP in energy efficiency does not reduce emissions with respect to current levels, there is potential for the allocation of avoided energy costs to support national development by improving social services, highlighting an important synergy between energy efficiency investments and socio-economic redistribution of wealth, and environmental preservation.
2. The North America analysis shows that stronger measures are needed to mitigate the impact of peak oil, which will impact society, economy and the environment both at the national (Canada, United States, Mexico) and regional level. Aside from peak oil, concerns are raised by the fact that the Energy Return on Investment (EROI) of conventional energy sources is declining, indicating that, on top of environmental concerns, depletion will soon be forcing the economy to a transition to renewable sources.
3. The U.S. National study provides information on the impact of increasing Corporate Average Fuel Economy (CAFE) standards and implementing Renewable Portfolio Standards (RPS). With respect to the former, T21-USA provides insights on the macro-economic impact of the so called “rebound effect” (Dimitropoulos, 2007), showing that increasing fuel efficiency may actually increase overall energy demand over the longer term. The RPS analysis on the other hand, indicates that increasing renewable energy generation will not drive the economy into a recession, as opposed to many studies made available in recent years and in accordance with latest studies. However, environmental side effects emerge due to the reduced consumption

of coal for electricity production, which reduces coal prices and increases its use in energy intensive manufacturing sectors, such aluminum and steel.

4. The analysis of selected U.S. sectors, such as public and freight rail transportation, shows that known and developed technology can play an important role in helping the U.S. reducing its dependence on oil while creating jobs and stimulating the economy. Important synergies in reducing emissions arise when coupling investments in electrified rail with the implementation of RPS provisions.
5. Finally, the study of the impact of climate change policies on the competitiveness of U.S. energy intensive manufacturing sectors shows that challenges may arise for the United States when introducing an emission cap-and-trade mechanism. Policy-driven increases in energy costs may have considerable impacts on certain segments of the manufacturing sector (e.g. aluminum and steel production). Investment opportunities have to be targeted early enough to mitigate negative impacts of rising energy prices by, among others, reinvesting the potentially avoided cost generated by energy efficiency improvements.

A summary of the insights gathered from the global, regional and national exercises is proposed in Section 6. This part offers an integrated overview of the value added provided by this study as a whole and by each case study separately.

Conclusions follow in Section 7. The final part of the study highlights (a) to what extent policy makers are equipped with tools that can support policy formulation and evaluation, while coping with uncertainty and complexity, and (b) what contribution the approach proposed and SD models, such as the customized T21 and MCM, can provide. The importance of representing the social, economic and environmental context, as well as the relevance of understanding the political context in which energy issues arise are proposed as the key factors to coherently and effectively support policy making.

In order to facilitate the understanding of the methodology and tools adopted for this study, three appendixes are added. Appendix A showcase a study of the performance of various customized T21 models that were developed by the Millennium Institute over the last 15 years.

Appendix B compares the results of the simulation of the models proposed in this study with models developed and used by the Energy Information Administration and the International Energy Agency. Appendix C provides a full documentation of the Ecuador, North America and USA models, including the customization of T21-USA modules (i.e. sub-sectors) to represent more in details the transportation and energy intensive manufacturing sectors.

2. Research Motivation

The present study aims at evaluating whether energy issues should be contextualized to effectively support policy formulation and evaluation. This implies (1) the analysis of the context in which energy issues arise, whether they be global, regional or national, and (2) the study of various policy options that are being considered for solving energy, environmental and national security issues. While the analysis carried out with conventional linear programming and optimization models is limited by narrow boundaries and lack of dynamics, computer simulation models based on System Dynamics can effectively support the analysis of both context and policies. The analysis carried out proposes the utilization of integrated energy models based on T21 and MCM. The use of these tools supports the analysis by providing an integrated framework to study the following characteristics of the policy-making environment:

- In spite of energy issues being global, regional and national, policy solutions are designed and implemented at the national level only.
- Despite interconnected and cross-sectoral energy issues, policies are narrowly focused on the energy sector while having an impact on society, economy and environment.
- 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.

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 society, economy and environment into a dynamic modeling framework.

- Building a model that serves to create dialogue and establish a mutual trust relationship with policy makers and stakeholders.

With the adoption of the Kyoto Protocol (UN, 1997) in 1997, national leaders have started investigating options for reducing carbon emissions within national borders. After ten years debating on 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.
The main motivation for the present study stems from the acknowledgement that there is a need for integrated tools 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).

The questions facing national leaders and policy makers are many and varied. According to the Union of Concerned Scientists, which released the Energy Blueprint for the United States back in 2001, the upcoming energy issues are connected to the social, economic and environmental development of the country. They identify the following main questions to be addressed by policy makers (UCS, 2001):

- Can the Government develop a national energy system that will provide security and jobs, and also leave a heritage of clean air, clean water, and pristine wilderness areas for the children and grandchildren?
- Can the Nation reduce carbon dioxide emissions, which threaten to destabilize the global climate, by developing a truly balanced portfolio of clean energy solutions that would allow to also having economic growth?

A first step towards these goals consists in examining the characteristics of the regional energy market and industry to identify trends in trade as well as foreseen national security risks in order to elaborate consistent, effective and sustainable policies at the national level. As an example, less than a month after President George W. Bush told the US in his January 31, 2006 State of the Union address that "*America is addicted to oil*" (G. W. Bush, 2006), the American Enterprise Institute (AEI) proposed a near-term solution for being less reliant on "unstable" sources of energy. AEI's suggestion consisted in encouraging resource-rich nations in the Western Hemisphere region to adopt sound policies for developing their oil and gas industries (Noriega, 2006), instead of searching for domestic solutions to the United States dependence on foreign oil, especially coming from the Middle East or critical states.

As part of the exercise of analyzing regional trends and contexts, particular attention is also given to a country's involvement in multilateral climate negotiations and to pressure from international competition. In the United States this is the case particularly for large emerging economies such as China, India, and Brazil that are not bound to reduce emissions under the current international climate framework (Houser et al., 2008). Of particular concern is the effect climate policy would have on carbon-intensive U.S. manufacturing, which will be addressed as a case study in this research (*Paper 5*).

As a second step, after having gathered information about regional energy availability and trade, policy makers and their advisors turn their attention to evaluating measures that would favorably impact the national economy and environment while addressing global energy issues. In April 2006, AEI released a second study, this time focusing on the national energy sector and natural gas. The AEI research concludes that if current global and regional trends continue, the United States may soon be facing shortages of natural gas and be threatened by the instability of exporting countries, as in the case of oil. In order to solve the larger problem of national security AEI suggests expanding domestic supplies, mentioning the positive effects on the U.S. economy and national security (Schmitt, 2006).

Various proposals to reduce energy consumption and support the shift to clean and renewable energy at the national level have been examined over the years. Generally, policy makers can use a "command and control" approach or formulate "incentive-based" policies (CBO, 2008). With respect to fossil fuel emissions the former would consist in introducing mandates on how much individual entities could emit or what technologies they should use; the latter would imply a tax on emissions or a cap on the total annual level of emissions combined with a system of tradable emission allowances.

The main options a government can choose from include actions in support of expanding and diversifying supply and reducing demand. Different instruments can be used, such as subsidies, incentives (e.g. feed-in tariffs), taxation and efficiency mandates. Governments can therefore support the development (1) and adoption (2) of energy efficient technology, as well as (3) facilitate the shift to cleaner energy sources. The general public and the industry can instead (4) reduce consumption by conserving energy, (5) adopt new and more energy efficient technology/appliances and (6) recycle waste that can be used for energy generation (e.g. electricity and biofuels) and production of commodities. As confirmed by various studies (EIA, 2005 and Lipp, 2007), similar policies and measures can be very effective in certain contexts, while being costly and un-efficient in others. Policy makers are now urged by global energy issues to find suitable and coherent national policies that would help moving toward a more efficient, less costly and less carbon intensive energy system. Despite the relevance of energy and environmental issues, some countries opposed to the ratification of the Kyoto Protocol, while others accepted and ratified it soon after its adoption on December 11th, 1997 and allowed it to enter into force on February 16, 2005. According to article 25 of the Protocol, it enters into force "*on the ninetieth day after the date on which not less than 55 Parties to the Convention, incorporating Parties included in Annex I which accounted in total for at least 55% of the total carbon dioxide emissions for 1990 of the Parties* *included in Annex I, have deposited their instruments of ratification, acceptance, approval or accession*" (UN, 1998). The first of the two conditions was reached on May 23, 2002 when Iceland, the 55^{th} Party, ratified the protocol. The ratification by Russia on 18 November 2004 satisfied the second clause and brought the treaty into force, effective February 16, 2005. To date the United States is a signatory country but has not ratified the agreement (UNFCCC, 2008), a position that shows little leadership and commitment in reaching goals of energy efficiency and reduction of emissions. As the EIA and Lipp study state, as further confirmation of what asserted in the United States by Colonel G. J. Lengyel, well designed policies will have to be accompanied by strong leadership and culture change, to successfully face complex and interconnected issues (i.e. environmental preservation, energy and national security), and reach the desired goals (Lengyel, 2007; EIA, 2005; Lipp, 2007).

Different governments evidently find themselves in different energy contexts that lead them to take dissimilar positions on energy issues (Lipp, 2007). Despite homogeneity in the energy demand and supply side is observed for most countries, with the identification of GDP and population as the main drivers for energy demand and of fossil fuels availability as the main factor influencing supply, the extent to which society, economy and environment shape policies and reactions to their implementation change from country to country.

Such reactions are perceived in different ways even within countries, with political parties often taking dissimilar positions on the same issues. Surveys, run in the United States in early 2007 by the National Journal, Washington Post, ABC News and Stanford University, indicate that there is little agreement on basic policy approaches within the U.S. Congress and that there is a clearer understanding among the population on what is needed. The National Journal has interviewed a sample of 113 members of Congress and results show that 95% of congressional Democrats and 13% of congressional Republicans say they believe that human activity is causing global warming; 88% of congressional Democrats and 19% of congressional Republicans would support mandatory limits on carbon dioxide emissions (National Journal, 2007). Out of 1002 adults nation wide, the Washington Post survey indicates that 86% think that global warming will be a serious problem if nothing is done to reduce it in the future and 70% think the government should do more than it's doing now to try to deal with global warming (The Washington Post, 2007).

In the United States, policy makers and the general public have access to a variety of studies analyzing specific legislation propositions, and, as expected, they are often showing contrasting results. The main agencies supporting policy making in the United States include:

- Congressional Research Service (CRS), which is a subsidiary of the Library of Congress. CRS produces reports on major issue areas as well as major legislation moving through Congress.
- The Government Accountability Office (GAO), a Congressional agency. This agency produces reports requested by Members of Congress and examines the effectiveness of government programs.
- Congressional Budget Office (CBO), a Congressional agency, is the Congressional counterpart to the Executive Branch Office of Management and Budget (OMB). CBO is the official budget "score keeper" providing estimates of the projected costs of legislation over the next 10 years, regular reports about the fiscal status of the federal government and cost trends of major programs.

There are in addition many "think tanks" and most of them have an ideological bent favored by one or the other, but hardly ever both parties. These include Brookings Institution (liberal-Democrats) and the American Enterprise Institute (Republicans). There are many boutique think tanks that focus on narrower policy issues, such as the Union of Concerned Scientists and Pew, which are trusted by

Democrats and distrusted by Republicans. The National Commission on Energy Policy (NCEP) is one of the few bipartisan organizations being trusted by both parties.

These agencies and think tanks, as well as governments around the world, generally use conventional approaches to analyze legislative proposals that are narrowly focused on a specific issue or sector, showing a disconnect with the need for integrated solutions. Among other tools, as one of the many inputs into the policymaking process, governments and the groups supporting them in policy formulation and evaluation might use computer simulation models. A "model" of this kind was defined as follows by a group of modelers and policy makers who met at a workshop organized by the Sandia National Laboratories in 2004 (Karas, 2004):

(1) A representation of a physical (or social, or both) system that in some way simulates the behavior of the system;

(2) May consist of a mentally manipulated set of concepts, a physical system, a mathematical description, a computer program, or some combination of these;

(3) May analyze (or solve) a problem, increase understanding of the system it simulates, forecast future states of that system, or predict the outcomes of measures taken to change the system.

It has to be noted that, even though a computer model simulates deterministic equations, its structure is based on mental models that should represent our understanding of how the system works, and the data models use are selected by the modelers. Furthermore, humans select the research questions and interpret the results. As a consequence, models can be erroneously used to support pre-existing conclusions and may result to be unsuccessful independently from their technical quality of analysis (Craig et al., 2002). Furthermore, King and Kraemer in 1993 found that: "*...models were used because they were effective weapons in ideological, partisan, and bureaucratic warfare over fundamental issues of public* *policy. Those models that were most successful, as measured by the extent of their use, were those that had proven most effective in the political battles over what kinds of economic and domestic policy should be followed, whether Democrats or Republicans should get the credit, and which bureaucratic agencies would receive the power and funds to implement the policies*" (King and Kraemer, 1993). Finally, they add a statement that seems still very relevant: "*Models are not of much use in times of ideological upheaval, simply because the decisions are based on beliefs rather than facts. Ideological policy makers appeal to their own versions of facts, and dismiss the facts of others as falsehoods. In this way, the fundamental assumptions of policy modeling are upended.*" (King and Kraemer, 1993).

In order for models to be defined and used successfully today, modelers and policy makers have to establish a relationship of mutual trust, which can be achieved when modelers account for the context in which policy making takes place (Karas, 2004).

With respect to energy, over the last few decades optimization tools have normally been employed to support policy decisions despite their many drawbacks (Martinsen, Krey, 2008). Such tools, of which the National Energy Modeling System (NEMS) (EIA, 2003) of the Department of Energy (DoE) is an example (others include MARKAL (Fishbone et al., 1983; Loulou et al., 2004), TIMES (Loulou et al., 2005), MESSAGE (Messner et al., 1996; Messner and Strubegger, 1995)), optimize energy supply to minimize production costs. Such models do not account for externalities or for the context in which issues emerge. When modeling and trying to understand interconnected energy issues, in order to provide consistent and valuable information to policy makers, the analysis should also be as integrated and comprehensive as their understanding of the issues is. This would allow taking into account and analyzing the context, both social, economical, environmental and political, in which issues emerge and possible elements of policy resistance that may arise in the future (Karas, 2004). In fact, the output of optimization tools consists of a snapshot of what the system would look like under perfect conditions (i.e. under perfect foresight) when a specific policy is applied (Sterman, 1998). Such models do not provide information on what path the system will follow to reach its optimum state, which is defined by a set of user defined constraints. This study proposes an approach that, in addition to representing the structure of the energy sector, incorporates social, economic, and environmental factors both in the analysis and in the modeling exercise and uses group modeling sessions to establish trust and confidence in the tools proposed.

These characteristics of the structure of models and their building process have been designed and implemented in this study to propose a set of tools that would allow policy makers to understand issues and systems, and gain insights into the impacts of actions under future uncertainty. These models are used to: (1) provide an integrated direct analysis and evaluation of policy choices; (2) generate projections of future developments (though acknowledging that long term accurate projection cannot easily be produced, even when simulating a large number of endogenous key variables (Sarewitz, 2000)); but also (3) increase the understanding of the relations underlying the system analyzed; (4) bring consistency in mental models. Improving mental models and increasing the understanding of systems supports the creation of a dialogue or a discussion on both model validity and issues being analyzed. In this respect, participatory modeling seems to be a very useful tool to build trust and confidence in the model because it lays out the characteristics of the framework used in a way that policy makers can interpret so as to eventually understand the rationale behind it (Karas, 2004).

Since the environment in which policies have to be implemented often influences policy makers (including the energy landscape of the nation/region, constituents' needs, implementation costs and advantages, and political agendas), the explicit representation of such a context may help identify what rationale drives the choice of legislators and, thereby, create dialogue and consensus among parties. The Sandia study indicates that "*the goal of modelers and policy makers should be a relationship of mutual trust, built on a foundation of communication, supported by the twin pillars of policy relevance and technical credibility*" (Karas, 2004). As a matter of fact, models used in support of policy making are involved in, and shaped by, the political debate and process. It is therefore important for all stakeholders to acknowledge the goals, constraints, and incentives the political and other contexts imply, to allow for the creation of understandable narratives in support of policy makers.

In order to evaluate whether energy issues should be contextualized to support longer-term policy formulation, their global, regional and national context will be explicitly represented in a simulation model. While conventional optimization models of energy systems can be parameterized to represent any national energy sector to optimize the cost of energy supply, they do not put energy issues into a context. Modern simulation techniques, such as System Dynamics instead, allow for the representation of the context by incorporating feedbacks, delays and nonlinearity into a flexible, transparent framework extending the scope of conventional approaches (Sterman, 2000). Furthermore, boundaries can be defined so as to help us formulate a coherent and realistic framework that enables us to understand what are the main structural factors upon which policy making is based. While these boundaries vary according to the level of aggregation (global, regional, national or state) and the energy issues considered, they should always represent reality by including social, economic and environmental dimensions, allowing for the identification of synergies and elements of policy resistance.

The contribution of this study consists of the evaluation of whether contextualizing energy issues is relevant to provide energy policy formulation support aimed at finding sustainable longer term solutions to the upcoming energy challenges. This research uses System Dynamics and proposes the utilization of various customized energy models integrated in the Threshold 21 and Minimum Country models, holistic frameworks that incorporate social, economic and environmental factors and their relations to the energy sector. These tools are used to better contextualize global, regional and national energy issues and are applied to case studies to investigate the longer-term performance of a selected number of policies under various scenarios.

The customization of the models to represent the context and the aggregated real functioning mechanisms of the energy sector in various case studies supports a better understanding of issues and serves as the basis upon which we may create a shared understanding and consensus among parties. The latter is reached through the use of participatory modeling and with the direct involvement of policy makers in the definition of the structure of the model and in the creation of alternative scenarios.

3. Research Approach

3.1 Introduction

This study aims at determining whether energy issues are context dependent through the creation of a set of integrated simulation models able to test the effectiveness of a variety of policies under different scenarios. Acknowledging that energy issues are global, connected to (and influenced by) climate change and national security issues, this study proposes a comprehensive approach to find answers to the research question mentioned above. This approach is designed to support the analysis of policy formulation and evaluation and follows the steps in identifying and packaging policy proposals by including (1) a global, regional and national investigation of energy issues, and answers the need of using integrated approaches by (2) incorporating the links between energy and society, economy and environment in a single framework.

Provided that GHG emissions are mainly influenced by carbon dioxide emissions, accounting for 73% of global emissions in the year 2000 (World Resources Institute, 2005), and that these emissions are mainly generated when burning fossil fuels, the energy sector becomes by right one of the major drivers for the upcoming climate change problem. Furthermore, when reviewing the geographical distribution of oil reserves it is not difficult to link it to failed states as well as historical and recent conflicts (Yergin, 1991). Energy, and especially fossil fuels, does therefore influence national security. On the other hand, the energy industry is highly vulnerable to both climate change and national security, especially for what concerns oil supply in current days. This makes the situation even more complex and identifies a two-way relationship between energy, climate change and national security. These three issues will be analyzed both in isolations and within an integrated framework with the help of case studies. In fact, complex problems such as climate change and the energy transition require a comprehensive research framework in which various dimensions are considered to contextualize energy issues. These dimensions are geographic, as the relevance of the issues analyzed ranges from global to national, and also multi-sectoral, acknowledging the contribution of feedbacks existing among society, economy and environment.

This study starts by investigating global energy issues using, and building upon, a global study: the Stern Review on the Economics of Climate Change (Stern, 2007). The Stern report, a report on the economics of climate change mitigation and adaptation, concludes that the cost of mitigating and adapting to climate change would be equal to 1% of global GDP, invested in energy efficiency and diversified supply for the next 50 to 100 years. Although many studies have attempted to calculate the cost of mitigating climate change (IEA, 2006), fewer researchers have analyzed the sources of the investment and the eventual allocation of the avoided energy costs.

The report also provides indications on how climate challenges can be effectively faced (Stern, 2007) and highlights strengths and weaknesses of Integrated Simulation Models (IAM) (Weyant et al., 1996 and Kelly, Kolstad, 1999). Sir Nicolas Stern identifies the presence of important exogenous assumptions (i.e. population and GDP) as one of the main weaknesses of IAMs and indicates that national integrated tools would be needed to evaluate the impact of national mitigation and adaptation strategies to climate change (Stern, 2007). This study aims at providing such tool, proposing an integrated framework that accounts for social, economic and environmental factors. The case study of the Republic of Ecuador, which represents the first part of this study, was chosen to analyze whether synergies can be found when allocating the investment indicated by the Stern report, and what would be the impact of reinvesting part of the avoided energy cost in social services to support longer term national development. In the case study of Ecuador, investment is mainly allocated to energy efficiency.

This choice originates from the analysis of the results of an on the ground study carried out by SolarQuest in the Galapagos, which shows that major energy saving can be achieved by substituting old appliances with new ones. By simulating a variety of national policies and investment options, the Ecuador model is an example that integrated tools can provide value added by complementing and extending the study carried out with global narrowly focused tools for climate change analysis.

The second step in this research aims at analyzing regional energy issues, the first area policy makers look at when defining national strategies. The case of North America was chosen, due to its high energy consumption, strong economy, large endowment in fossil fuels and also for the long trading history between Canada, Mexico, and the United States (EIA, 2007). A variety of scenarios on energy availability will be simulated to analyze the impacts of declining world oil production on emissions, trade dynamics and economic growth. Since global responses to global challenges emerge from national policies in leading countries (RFF, 2007), various policy proposals are also tested for the United States under different oil constrained scenarios to evaluate the extent to which these legislations would contribute to reducing the vulnerability of the country to oil and liquid fuels.

After having analyzed selected energy issues from a global and regional perspective, the research continues with a more detailed study of the impacts of energy policies at the national level. The case of the United States of America was chosen to support the analysis of policy formulation and evaluation by incorporating the assumptions of different studies in an integrated framework, and by testing the impacts of various policy proposals on a variety of cross-sectoral indicators.

While issues related to energy availability and trade were analyzed at the regional level, the national studies hereby proposed mainly focus on energy and national security (i.e. transportation, US Congress, 2007), as well as climate proposals and international competition (Houser et al., 2008).

The transportation case study focuses on the impact of electrifying urban and freight rail as a mean to reduce oil consumption in the United States using known and mature technology, answering the concerns raised by Brown and Huntington (Brown and Huntington, 2008). For what concerns freight rail, 34,500 miles of strategically relevant diesel rail tracks are assumed to be converted to electrified rail, improving national security and vulnerability to liquid fuel scarcity. Regarding urban rail, transit oriented development (Arrington, 2003, Vuchic and Vukan, 2007) and the creation/extension of subways and streetcars coverage are tested. Synergies are explored when coupling electrification of rail and investments in renewable energy, to supply the increasing electricity needs that would otherwise be obtained using thermal generation.

The study of climate proposals focuses on the impact of selected legislative proposals on selected energy-intensive manufacturing sectors (i.e. aluminum, steel, paper and chemicals), to better investigate whether the concerns that have prevented the U.S. from ratifying the Kyoto Protocol are well founded (EIA, 1998; Global Energy Services, 2005; Scott, 1997; Standard & Poor, 1998; CEI, 2007). This analysis therefore focuses on the national manufacturing sector, but includes elements of international competition.

Proposals on energy efficiency (e.g. CAFE), diversification of the energy supply mix (e.g. RPS), as well as the provision of subsidies (e.g. corn ethanol) were also simulated to better understand whether the U.S. is moving towards achieving a leadership role in solving energy and climate issues. While the simultaneous implementation of most of these policies have been already analyzed (Logan, Venezia, 2007) and simulated with NEMS (EIA, 2003). The study hereby proposed updates and extends the exercise carried out by the Department of Energy by including the context in which such policies will be implemented, represented by society, economy and environment.

As previously mentioned, the hereby presented approach is designed to support the analysis of policy formulation and evaluation and follows the steps in identifying and packaging policy proposals by including (1) a global, regional and national investigation of energy issues, and answers the need of using integrated approaches by (2) incorporating the links between energy and society, economy and environment in a single framework.

This research was largely carried out in Washington D.C. and involved consultations and group modeling sessions with various institutions (e.g. Federal and State Government, as well as various agencies), think tanks (both Democratic, Republican and non partisan) and experts (e.g. engineers, economists and researchers of various disciplines).

Since models are embedded in the policy debate and process and policymakers are more likely to make use of analyses that come from modelers whom they have come to trust (Karas, 2004), working in Washington D.C. proved to be very useful in understanding the political context in which energy issues are faced and supported the correct creation of the model as well as the effective dissemination of their results.

The main characteristics of the modeling process adopted include (a) a participatory approach in defining the structure of the models and (b) in supporting policy formulation. As a consequence, both the approach and tools were used to (c) create dialogue and (d) consensus on energy issues by explicitly comparing the numerical and structural assumptions of different studies. By incorporating various theories and thanks to its comprehensive scope, this study helps increasing the understanding of why issues arise and what possible synergies and elements of policy resistance may come by, while building trust and confidence in both the approach used and the results of the model.

The main guidelines to increase relevance and credibility followed during the development of the research when communicating and interacting with policy makers were gathered from the Sandia study, and include (Karas, 2004):

Guidelines for Enhancing Communication

1. Understand the context: it is very important to understand what the use of the model will be and what are goals and constraints that policy makers are dealing with. This can be achieved through reading newspapers, attending public events and joining online discussions.

2. Explain Clearly: as researchers trained in different methodologies have problems in communicating effectively their methods and results, communicating with policy makers that rarely have a deep technical knowledge of the issues being analyzed can be a challenge. Modelers have to learn "different languages" to communicate effectively and provide answers that policy makers can understand and use and are responsible for establishing an effective working relationship with policy makers and stakeholders.

3. Attempt continuing dialogue: since policy makers are always very busy and the political debate can shift very quickly, establishing a continuous and very effective dialogue was very important to make sure that the analysis is on target and to keep high interest in the modeling exercise.

Guidelines for Being Relevant

4. Find the relevant audience: in order for a study to be successful, the right "sponsors" and interested parties have to be identified. This was done by organizing a public event on T21-USA, to which a variety of groups were invited. Some of them eventually showed interest and provided many opportunities to give presentation to more diverse audiences.

5. Address the purpose: J. Sterman (Sterman, 2000) states that a model should always be built for a purpose. This purpose was always explicitly mentioned to the audience and was agreed upon when the development of models involved other parties, such as in the case of Ecuador, North America, and the model detailed

transportation and energy intensive manufacturing sectors studies.

6. Focus on the problem, not the model: a model alone, even when of top technical quality, does not represent value added. Its results, when insightful and presented correctly, are instead useful information to policy makers.

7. Don't assume the impossible: reasonable scenarios where agreed upon with stakeholders and interested parties and the simulated results were then shared to make sure they were realistic.

8. Tell a story that makes sense: the use of System Dynamics allows for the creation of coherent stories that can be communicated clearly to other parties.

9. Recognize time constraints: models are always a continuous work in progress. Time constraints have to be taken into consideration to comply with deadlines and provide policy makers with useful information when they need it.

Guidelines for Establishing Credibility

10. Pay attention to reputation: policy makers usually prefer to work with experienced modelers. Given the limited experience of the author in the US political environment, particular attention was devoted to acknowledging limitations of the models and methodology, providing transparent analysis and methods and involving reviewers.

11. Don't overreach: instead of using existing models to support policy analysis, the author created customized models tailored around the issues to be analyzed and policy choices currently being discusses.

12. Acknowledge data limitations: extensive data collection took place for each of the case studies proposed, but updated and coherent information was not always available. Policy makers and stakeholders were made aware of this issue and supported both data collection and the analysis with useful inputs.

13. When predicting, show track record: sensitivity and uncertainty analysis were carried out in addition to provide an explanation of what the main causal relations

responsible for the creation of past behavior of the system were. The use of System Dynamics helps considerably in these tasks.

14. Simpler is better: while larger models can provide insights on many research areas, they may not provide additional value added with respect to the use of a simpler model. For this reason the research hereby presented proposes both complex (North America and USA) and simpler (transportation and energy intensive industries) analyses that aim at both raising awareness about energy issues and support the simplified though detailed analysis of some of them. The results of the simulations, especially for what concerns larger models, were carefully selected to represent what the audience perceived as valuable

15. Compare and collaborate: policy makers and stakeholders are often not experts in modeling methodologies. It is a modeler's responsibility to compare his own approach to others and inform the parties involved on how they compare to each other. Considerable background research as well as learning about, and participating to, the Stanford Energy Modeling Forum (EMF) has greatly helped in this.

In addition to creating dialogues and proposing a tool to better understand the underlying causal relations driving the behavior of a system, the main contributions of this study and approach to current research include an integrated analysis of the impacts of (1) increasing energy efficiency to reinvest the avoided costs in social services in developing countries, peak oil on (2) emissions, (3) the economy and on (4) the Energy Return on Investment (EROI). In addition, this research contributes to the study of the cross-sectoral effects of (5) improved Corporate Average Fuel Economy (CAFE) standards on the economy (i.e. rebound effect (Dimitropoulos, 2007)), (6) Renewable Portfolio Standards (RPS), (7) cap-and-trade proposals, (8) investments in electrifying rail while (9) increasing the understanding of whether national security and climate strategies are compatible and complementary, (10) subsidies to ethanol and (11) its contribution to the transportation sector. These will be presented more extensively in sections 4 and 5.

In the following section the geographical dimension is used to present the case studies analyzed in this research. The contextualization of energy issues is also highlighted, and a brief anticipation of the results is provided.

3.2 A Geo-political View of the Energy Sector

3.2.1 Global Perspective

From a global perspective on energy issues, climate change is the major challenge policy makers have to address in the years to come. A conclusion of the Stern Review on the Economics of Climate Change (Stern, 2007) is analyzed through the customization of the model to the Republic of Ecuador, a net exporter of oil with heavily subsidized fossil fuel energy prices (Peláez-Samaniego et al., 2007). This case study is used to investigate the social, economic and environmental consequences of investing 1% of GDP to stimulate the adoption of energy efficient technology, the allocation of subsidies to reduce electricity prices and investment in renewable energy electricity generation.

Particular attention is devoted to the potential for increased energy efficiency, which is based on a detailed study carried out on the ground by SolarQuest in the Galapagos. Such study examines the potential efficiency gain obtained by replacing old appliances with more efficient ones and accounts for factors such as the lifetime of appliances and the income level of the population, which are among the most important factors influencing the effectiveness of policies aiming at increasing residential energy efficiency (Young, 2007).

Since the Stern Report is a global study that derives conclusions on policies and actions that can be applied at a national level, the Ecuador study serves to evaluate to what extent such a global report can provide useful inputs for a country energy policy planning study, but also extends the analysis carried out by the Stern report for the Ecuadorian context building on the results of the report, and answers some of the concerns expressed by Sir Nicolas Stern on the modeling tools used by his team.

Global energy issues involving climate change generate regional concerns (e.g. electricity losses from glacier melting) and are characterized by very different contexts, though they may be generated by the same global causes. Policies aimed at solving these issues have different time frames and scopes, and are strongly related to local geography and society.

Ecuador has gone through rapid development over the last 15 years, with the only economic slow down taking place in correspondence of the Latin American financial crisis of 1999. Since 1990 Ecuador's GDP grew by 50% and unemployment is currently estimated to be around 10%. Real disposable income during the same period of time has increased by only 10% (BCE, 2007), while population grew by 30% (UN, 2007). The latter is mainly due to decreasing fertility rates and increasing life expectancy.

Total energy consumption in Ecuador, which is one of Latin America's largest crude oil exporters, has increased by 60% between 1990 and 2007 (EIA, 2007). Electricity consumption rose by 50% mostly supplied by the larger use of fossil fuels. As a matter of fact, the oil sector is predominant in energy supply (accounting for about 80% of total energy consumption, with about 86% of total energy supply originating from fossil fuels) as well as in the Ecuadorian economy, accounting for about half of total export earnings and one-third of all tax revenues (EIA, 2007). Hydroelectric power generates about 45% of electricity consumption, while 44% is thermal and 11% imported (Peláez-Samaniego et al., 2007). As in the case of oil refining, which is limited, natural gas consumption is constrained by the absence of proper infrastructure. Per capita energy consumption has increased by 22% over the last few years and emissions are 67% higher than in 1990.

Results of the simulation suggest that investing 1% of GDP in Ecuador will not reduce emissions below 2007 level. This general analysis leads to the conclusion that different countries would react differently when investment in energy efficiency are allocated, as mentioned in the Stern report. The differences existing among countries and the different dynamics driving society, economy and environment make so that technologically advanced countries could contribute more than proportionally to the commercialization and adoption of efficient appliances, leading to a reduction in emissions. Furthermore, results of the simulation show that the proposed allocation of subsidies to electricity prices promoted by President Correa may result to be useful at the political level, but will not generate positive outcomes for the Ecuadorian private and public sectors.

3.2.2 Regional Perspective

Despite differences in political leadership and economic structure, different countries and regions have often similarities in energy availability and infrastructure. In other cases, when a variety of energy sources are available only among neighbor countries, trade components are very relevant to shape national energy policies, such as in North America. The author chose to analyze this region because of its unusually heterogeneous mix of countries, which includes few among both the most important consumers and producers of conventional and unconventional energy (EIA, 2007). In this study USA, Canada and Mexico are compared to understand what an oil constrained future may imply for these countries, currently heavy importers (e.g. USA) and net exporters (e.g. Mexico) of energy. An analysis of whether the policy being formulated and discussed nowadays is adequate to solve such issues, especially for the U.S., is proposed.

Canada and Mexico have gone through rapid economic development over the last 15 years, with the only exception of 1991 for Canada (due to the worldwide economic recession of the early 1990s) and 1995 for Mexico (due to the collapse of the new peso in December 1994). Since 1990, the GDP of both countries grew by more than 50%, while total population rose by 24% in Mexico and 17% in Canada (EIA, 2007). The faster growth of Canadian economic activity relative to population is due to increasing literacy rates, which generally provide higher salaries. Because of higher GDP, energy consumption in Canada has greatly increased over the years, especially for what concerns natural gas (+42%), electricity (+29%) and oil (+30%) (EIA, 2007). The use of coal instead has decreased by 3% from 1990. In the case of Mexico, different income distribution and technology have determined a very different scenario from Canada: coal and natural gas demand have doubled, while electricity demand has increased by 88%. Oil consumption has increased only by 11%. Conventional thermal electricity generation has increased in both countries, more than doubling in Mexico (+133%) and growing by 40% in Canada. As a consequence, greenhouse gas emissions have increased by 48% in Mexico and 37% in Canada with respect to 1990 levels.

The largest source of energy consumption in Canada and Mexico is oil (31 and 59% respectively). Natural gas is an important energy source in both countries, representing 24% in Canada and 27% in Mexico. Canada extensively uses hydroelectricity (25%) and by a lesser extent coal (12%) and nuclear (7%). In Mexico all other fuel types, aside from oil and natural gas, do not significantly contribute to energy supply.

Both Canada and Mexico have considerable amount of fossil fuels and are among the world's largest producers and exporters of energy. The U.S. receives most of Canada's energy exports, which have increased over time. Mexico on the other hand, the sixth-largest oil producer in the world in 2007, is facing issues due to the decline of the giant Cantarell oil field (Reuters, 2008). As in the case of other oil

exporting countries, the oil sector is a crucial component of Mexico's economy as it generates about 30% of total government revenues.
Energy trade has evolved differently in these two countries. While Canada has managed to keep coal exports somehow constant over time (increasing exports again recently), Mexico is now a net importer of coal. Similarly, Canada has managed to double exports of natural gas with respect to 1990 while Mexico is now a net importer (though it is still a small portion of energy consumption). For what concerns oil, the assessment is reversed as Canada is a net importer (+150% with respect to 1990) and Mexico is a net exporter (+50%).

The results of the simulations show that, in an oil constrained future, trade balances among USA, Canada and Mexico will change significantly, mainly due to decreasing production of conventional fossil fuels in Canada and Mexico. In addition, the simulation of assumptions on oil availability provided by the Association for the Studies on Peak Oil and Gas, U.S. Chapter (i.e. world oil will unexpectedly decline in 2011), indicates that actions need to be implemented soon in order to mitigate the negative effects of reduced availability of liquid fuels (NPC, 2007; Stern, 2007). In fact, negative impacts on GDP and disposable income are projected to reduce private and public investment, triggering a recession and therefore reducing the potential to invest in renewable energy and social services (e.g. social security and medicare).

3.2.3 National Perspective

Despite global and regional energy trends and dynamics seem to be relevant in defining energy policies, national needs are the main responsible drivers for reforms in the domestic and consequently international energy system (RFF, 2007). The U.S. is the largest energy consumer as well as the richest country in the world (CIA, 2008). America's economic growth, fueled by the availability of cheap energy, has driven global economic growth for the last few decades, but it is now challenged by fast growing developing countries and a frozen credit market. This is a unique context, where the world's largest economy can serve as example for other countries to move forward a cleaner and less carbon intensive society, turning threats into opportunities. Similarly, developing countries, such as China, find themselves in very peculiar contexts, relying on the U.S. currency and being interested in keeping the U.S. economy wealthy, while competing for the same energy sources. Consequently, the U.S. case is particularly controversial and interesting both for what concerns the domestic debate on energy issues (see National Journal, 2007 and The Washington Post, 2007) and international economic equilibria.

A general overview of the U.S. energy future prospects is presented as part of this study in addition to the analysis of recently -and soon to be- discussed energy bills (e.g. Corporate Average Fuel Economy Standard -CAFE-, Renewable Portfolio Standards –RPS- and subsidies to biofuels).

The U.S. experienced the fastest economic development in North America over the last few decades. GDP grew by 63% between 1990 and 2007 (BEA, 2008) while population has increased by 18%, reaching 300 million in 2005 (UN, 2007). Total energy demand increased by 20% in the same period, while supply has remained just about flat, leading imports to increase by 56% (EIA, 2007). As a consequence of increasing energy consumption, emissions are now 15% above 1990 level.

The demand for oil (40% of total energy consumption) has grown since the oil crisis in the late 70s and early 80s. Coal (23%), natural gas (22%), nuclear 8% and renewables (6%) follow crude oil and derivates, to complete the energy demand portfolio of the U.S. Concerning energy supply, oil has declined from 30 to 19%, coal, natural gas and renewables are somewhat stable (32, 28 and 8% respectively), while nuclear increased from 3 to 11%. The most energy intensive and consuming sectors are transportation, which represents 38% of total demand

and grew by 30% in absolute terms between 1990 and 2007, and industry, which accounts for 34% of total energy demand (and has seen its share of total consumption decrease lately due to the relocation of a number of energy intensive manufacturing sectors overseas). The commercial (11%) and residential sectors (15%) are relatively less energy intensive.

Results of the U.S. study indicate that the implementation of higher CAFE standards, when applied in isolation, generates emissions reductions below expectations over the longer term. In fact, per capita consumption of oil is projected to increase in the medium to longer term due to higher savings (e.g. avoided costs from motor gasoline consumption), which allow households and the economy to increase consumption, hence GDP, consequently triggering an increase in energy demand. This is known as rebound effect, analyzed here both at the macroeconomic and sectoral level (this impact was not extensively analyzed with an integrated framework yet (Dimitropoulos, 2007; Musters, 1995)). Such an effect raises concerns on the validity of the CAFE policy for climate change mitigation and this example attests the importance of creating synergies among policies and applying comprehensive and consistent energy regulations. In the case of CAFE standards, where the economic context is geared towards consumption, synergies would be found by providing greener energy supply alternatives such as those spurred by the implementation of Federal Renewable Portfolio Standards. Alternatively, increasing CAFE standards results more effectively when also oil prices are projected to increase, indicating that the impact of policies also depends on the assumptions and market scenarios simulated. The integrated model customized to the U.S. accounts for the impact of oil prices on miles driven and on the car stock, two relevant endogenous factors in T21, analyzed in depth in a 2008 report by the Congressional Budget Office (CBO, 2008).

In addition to policies being currently discussed by House and Senate, a further investigation of the U.S. energy context in the transportation sector is proposed. While most of the public discussion on climate change is concentrated towards the identification of technologically advanced “silver bullets” able to solve the energy and climate crises, the author proposes the analysis of mature technology that would naturally fit within America’s energy context.
This case study investigates the creation of a more efficient transportation system based on electrified urban and freight rail, similar to what France, Germany and Switzerland have done in recent years. The contextualization of the transportation sector (1) provides useful insights, (2) answers some of the concerns raised by Brown and Huntington (Brown and Huntington, 2008), by linking the history of urban light rail to contemporary national security issues, and (3) incorporates relevant emerging factors in city planning, such as energy-efficient zoning and transit oriented development (Friedman, 2006). The results of the study show that, as in the case of CAFE standards, electrification of rail alone would not produce benefits in terms of the reduction of carbon emissions in the longer term. Renewable energy generation capacity has to be put in place to avoid an increased utilization of coal for electricity generation, eventually consumed by 34,500 miles of upgraded rail.

A similar integrated analysis is carried out at the sector level, where the impact of cap-and-trade policies is analyzed for U.S. energy intensive manufacturing industries. In such case, the author investigates the effect of increased energy prices (induced by the implementation of a cap-and-trade legislation) on the cost structure of the aluminum, steel, chemical and paper industries, additionally investigating foreign competition and investment opportunities. The proposed case study therefore combines the national and global dimensions of U.S. manufacturing industries by considering world markets and their effects on the profitability of domestic producers and environmental preservation. Results of the simulation and analysis show that the aluminum and steel sectors may require considerable restructuring to remain competitive in the global markets, due to their heavy reliance on carbon intensive energy sources. While the paper sector has potential to reduce energy intensity through the adoption of energy efficient technology, the chemical sector may need to rely even more on electricity given its mature processes and technology. Insights emerge also from the analysis of direct use and of feedstock energy, as well as from the study of cost pass-along options. These may allow industries to keep high operative margins in the short term, but are likely to reduce their market share over the longer term.

3.3 Characteristics of geographical energy contexts: Complexity

Various energy contexts are unique in different geographical areas. A wide range of properties ranging from political environment to richness of natural resources characterizes these contexts. When reducing them to a simulation models, boundaries are set. These apply to the geographical area analyzed, the socio-economical dimensions of the society scrutinized and, in our specific case, the depth of the representation of the energy industry. In order to represent such 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. The approach proposed by the author aims at decoupling the properties of the real social systems analyzed, in order to better understand how the underlying structure of the system generates its behavior. 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*" (Roberts et al., 1983). 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 exceptional profits of oil exports, the government has decided to further subsidize domestic gasoline prices as world oil prices increase (Bradsher, 2008)). This mechanism helps keeping social cohesion and government support. On the other hand, such intervention generated a series of side effects: the lower the domestic price of gasoline, the higher the 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 abroad by international players, 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 profitability of domestic production.

The example above identifies a negative feedback loop, where high profits lead to a decrease of future profits due to increasing domestic demand. Such loops tend towards a goal or equilibrium, balancing the forces in the system (Forrester, 1961).

A feedback can also be positive, when an intervention in the system triggers other changes that amplify the effect of that intervention, reinforcing it (Forrester, 1961). 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 (Forrester, 1961). 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 to identify side effects, elements of policy resistance, and eventually synergies that would make policies more effective. For instance, simulating improved CAFE standards in isolation indicates decreasing future consumption of motor gasoline. Adding feedbacks helps identifying an important element of policy resistance: reducing consumption of motor gasoline decreases households' expenses making more resources available to them, 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 to anticipate what is know as Jevons Paradox (Jevons, 1865), or rebound effect (Dimitropoulos, 2007; Musters, 1995), 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*" (Forrester et al., 2002). 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 of, 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" (Forrester, 2008).* Secondly, when the short-term performance of the system is negative or below expectations, which is usually 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 strategy, very common in our present political structures and mainly driven by short-term pressures and agendas, prevents the system from effectively adjust to the proposed interventions and improve over the longer term. Most policy proposals that are indeed focused on short-term interventions have little 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 possibly needed mitigating actions that allow the system to move in the desired direction (e.g.

when the cost of positive longer term interventions create 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 (Hirsch, 2005), 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, 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.

In addition to the uncertainty about the timing, mainly due to the scarcity of reliable information on oil reserves and resources, the implementation of mitigating actions and their effects are also characterized by delays. Dynamic quantitative studies are therefore needed to address the upcoming issues related to peak oil and its potential impacts on society, economy and environment.

Complex systems are characterized by non-linear relationships that cause feedback loops to vary in strength, depending on the state of the system (Meadows D., 1980). 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 raptures 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.

3.4 Energy Planning: Methodologies and Tools

3.4.1 Methodologies Review

A variety of factors have to be investigated when analyzing energy policy options for a specific geographical context. These include the availability of energy sources, such as fossil fuels and the structure of the industry in place (e.g. supply), as well as market demand. Supply has generally been represented through the utilization of models that could reproduce detailed complexity very accurately.

These include the MARKAL family of models (Fishbone et al., 1983; Loulou et al., 2004), which respond to a question particularly important to producers: how to minimize production cost while supplying the energy demanded to the market? Such models have been often applied to national contexts, in which the main objective question/function was translated into: what is the best portfolio of energy supply that allows for the smallest energy production and delivery cost? (IIASA, 2001 and 2002). The structure of such models is very detailed and takes into account primary energy sources as well as secondary ones, representing every step of the conversion process of various energy forms (Loulou et al., 2004). New scenarios are generally generated by using different parameterizations for different geographical areas analyzed. The structure of the model can be modified according to the availability of energy sources and processes used in the selected area of study, and a modular approach is usually adopted (Loulou et al., 2004). The main results offered include the optimum production mix and its associated production costs. With energy demand and prices being in most cases exogenous, the scenarios simulated lack the dynamic analysis of the market and miss the representation of major events that influence energy markets (Freedman et Al., 1983), generating results that are not always accurate (O'Neill, Desai, 2005 and Winebrake, Sakva, 2006).

As mentioned in the previous section, adding feedback loops, non-linearity and delays allows incorporating dynamic components of the market to the simulation tools utilized. 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. The identification of such processes is not as straightforward as in the case of detailed complexity analysis and representation, nevertheless the customization aimed at representing dynamic complexity can adds to the accuracy of demand and prices calculation, which are the main input to conventional supply optimization tools. 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.

Every methodology, as well as its applications, has strengths and weaknesses. These 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 (Stern, 2007).

Optimization, econometrics and simulation are here presented. 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*" (Sterman, 1998), are normative, or prescriptive, models. In fact, these models provide information on what to do to make the best of a given situation (the actual one) and do not generate insights on what might happen in such situation or what the impact of actions may be. Policy makers often use optimization tools 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 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 (Sterman, 1998). 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 (IIASA, 2001 and 2002).

The challenges related to optimization models include the correct definition of an objective function, the extensive 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 (Fishbone et al., 1983; Loulou et al., 2004) and MESSAGE (IIASA, 2001 and 2002) provide snapshots of the optimum state of the system with time intervals of 5 or 10 years. 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 very short-term time frames. When analyzing the impact of policies in social, economic, and ecological systems, on the other hand, longer time frames are required, limiting the usefulness of optimization techniques.

Econometrics measures economic relations, running statistical analysis of economic data and finding correlation between specific selected variables. Econometric exercises include three stages – specification, estimation, and forecasting (Sterman, 1998). 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). Econometrics uses economic theory to define the structure of the model (e.g. a Cobb-Douglas production function can be used to forecast GDP). The quality and validity of projections is therefore highly connected to the soundness of the theory used to define the structure of the model.

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. The analysis of unprecedented events or policies that have never been applied before leaves room for uncertainty given that econometrics do not provide insights on the mechanisms that generate changes in the system.

While optimization models are prescriptive and econometric models do not provide insights on the functioning mechanisms of the system analyzed, simulation models are descriptive and focus on the identification of causal relations influencing the creation and evolution of the issues being investigated. Simulation models are in fact "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.

Simulation models aim at understanding what the main drivers for the behavior of the system are. 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. The results of the simulation would then show the existence of correlations in a dynamic manner, which are the outputs of an econometric analysis. On the other hand, the main assumptions of simulation models are those causal relations forming the structure of the model: instead of using economic theories, simulation models represent theories of how the system actually works. In other words, 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 such models takes place in different stages, and the most peculiar tests when compared to optimization and econometrics, is the direct comparison of projections with historical data, which simulation models can backtrack, and the analysis of structural soundness with respect to reality (Barlas, 1996). Potential limitations of simulation models include the correct definition of boundaries and a realistic identification of the causal relations characterizing the functioning of systems being analyzed.

3.4.2 Models Review

A large number of models are available for either analysis of energy or integrated national planning. Unfortunately, only few of them encompass both aspects in a single holistic framework. Feedbacks across the economy, society, and environment are difficult to identify, manage, and quantify, especially with conventional methodologies and models. Two categories of energy-economy models are commonly accepted: market and behavior-oriented, which are both causal-descriptive (e.g. System Dynamics) or correlational (e.g. econometrics), and bottom-up optimization models (Bunn and Larsen, 1997). Policy optimization models are generally built to find the optimal intervention that minimizes expected energy supply costs at any point in time, given a specific set of assumptions and constraints (Sterman, 1998). Correlational models provide projections on the implementation of policies describing the system using correlation and being based on established economic theory (Sterman, 1998). System Dynamics models instead provide information on the functioning of the systems to analyze the wider impacts of each policy being tested (Sterman, 2000). These policy proposals are taken as given to support the formulation of final drafts and evaluate their impacts on society, economy and the environment, without imposing rational behavior or economic equilibrium.

System Dynamics models thus have more freedom to represent phenomena that are inconsistent with some of the assumptions (i.e. economic theory) of policy optimization models, allowing a full customization of their structure through the representation of feedbacks, delays and nonlinearity.

Early energy models were commonly linear programming applications focused strictly on the assessment of energy systems. Some of these models are still being used, despite their limited scope (Martinsen, Krey, 2008). Some linear programming models were then further developed to include non-linear programming components that allow for the interaction of "bottom-up" technology modules with "top-down" simplified macro-economic modules (Loulou et al., 2004; Messner and Schrattenholzer, 2000). Recently, due to the need to investigate the impacts of natural disasters, as well as technology development, these tools were enhanced with stochastic programming and mixed integer programming techniques (Loulou et al., 2004). Models like MARKAL (MARKet ALlocation) (Fishbone et al., 1983; Loulou et al., 2004), MESSAGE (Model of Energy Supply Systems Alternatives and their General Environmental Impacts) (Messner et al., 1996; Messner and Strubegger, 1995), WEM (World Energy Model) (IEA, 2004) and NEMS (National Energy Modeling System) (EIA, 2003) belong to the category of models that have evolved over time and now include econometric components and a Computable General Equilibrium model (theory based) to take into account macro-economic conditions, on top of an optimization structure representing the energy system. MARKAL in particular, which nowadays represents a family of models more than a single framework, is in fact a "*partial equilibrium bottom-up energy system technology optimization model employing perfect foresight and solved using linear programming; with numerous model variants that expand the core model to allow for demand response to price (MACRO (non-linear) and Elastic Demand (MED)), uncertainty (Stochastic), endogenous technology learning (ETL), material flows and multi-*

region (linked) models; plus new variants under development which support multi-criteria analysis (Goal Programming), and myopic execution (SAGE for EIA IEO)" (Loulou et al., 2004).

The use of medium to longer term energy planning models over the years has provided policy makers and planners with insights on policy impacts and energy technologies, in addition to offer projections on demand and supply as well as prices. 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 (e.g. causal descriptive models). These models, such as in the case of WEM, include six main modules: final energy demand; power generation; refinery and other transformation; fossil-fuel supply; CO_2 emissions and investment (IEA, 2007). 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 (Loulou et al., 2004).

Each model in this category slightly differs from the others in terms of details and boundaries. MESSAGE, for instance, finds the optimal flow of energy from primary energy sources to useful energy demand (end-use consumption), through the simulation of various investment choices that lead to the lowest cost of all feasible energy supply mixes to meet the specifically given energy demand. In other words, given exogenous demand, MESSAGE selects the energy mix that supplies it at least cost (IIASA, 2001 and 2002). The World Energy Model instead calculates energy demand econometrically, using data for the period 1971-2004. For future assumptions, adjustments can be made to account for expected changes in structure, policy or technology, using econometrics (IEA, 2004). 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 and energy prices. In order to calculate demand and other macro variables in such way, economic growth and demographics have to be indicated exogenously, in addition to technology costs, technical characteristics (e.g., conversion efficiencies) and development (IIASA, 2002; IEA, 2004).

The combination of MESSAGE and MACRO produces similar results that fully integrated models generate. These 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 (Institute of Computers and Communications Systems National Technical University of Athens, 2006), POLES (LEPII-EPE, 2006) and PRIMES (NTNUA, 2005 and 2006) models belong to this category. General equilibrium models (CGE) and partial equilibrium models allow for consistent comparative analysis of policy scenario, by ensuring that in all scenarios, the economic system remains in general equilibrium. This, though, adds important assumptions to the models, which are now integrated energy-economy models: 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 (Fiddaman, presentation to EMF, 2007).

In the case of MARKAL (Loulou et al., 2004), the output of the model is a supply-demand equilibrium that minimizes the net total cost of energy supply while satisfying a number of constraints (which is characteristic of the optimization component of the model). MARKAL computes partial equilibrium on energy markets, which means that the demand and supply of various fuels are in equilibrium through prices (i.e. prices as so that quantities produced in each time period are exactly the quantities demanded by the consumers).

A more comprehensive model that incorporates a larger number of economic components with respect to MARKAL is GEM-E3 (General Equilibrium Model for Energy-Economy-Environment interactions). This model computes the equilibrium prices of goods, services, labor and capital that simultaneously clear all markets, and determines the optimum balance for energy demand/supply and emission/abatement (Institute of Computers and Communications Systems National, Technical University of Athens, 2006).
The GEM-E3 Model 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. 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 (Drud et al., 1986). 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 (Institute of Computers and Communications Systems National Technical University of Athens, 2006). The main exogenous inputs to the model are population, GNP and energy intensity.

The wider boundaries of the GEM-E3 model resemble the structure of T21, a causal-descriptive model, where System Dynamics (SD) is employed and where society, economy and environment are represented. 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. Examples of SD models applied to energy issues include the IDEAS model (AES Corporation, 1993), an improved version of the FOSSIL models (Naill, 1977; Backus, 1979) built by Roger Naill, the Energy Transition Model (Sterman, 1981), the Petroleum Life Cycle Model (Davidsen, Sterman and Richardson, 1988 and 1990), and the Feedback-Rich Energy Economy model (Fiddaman, 1997). These models do not encompass the interactions between energy, society, economy, and environment, which constitute one of the major innovations introduced by the Threshold 21 model. In fact, FOSSIL, IDEAS and the Life Cycle models consider energy in isolation, Sterman's model includes energy- economy interactions only, and Fiddaman's FREE model focuses on economy-climate interactions[4]. Nevertheless, both FOSSIL and IDEAS models made important contributions, such as their use by the Department of Energy for policy planning in the eighties.

A recent System Dynamics model used as part of an Integrated Assessment Models (IAM), IMAGE 2.2, for climate change analysis is TIMER (Loulou et al., 2005, Dutch National Research Programme on Global Air Pollution and Climate Change, 2002). TIMER is a simulation model that does not optimize scenario results over a complete modeling period on the basis of perfect foresight, but simulates instead the year-to-year investment decisions based on a combination of bottom-up engineering information and specific rules about investment behavior,

[4] Oil and gas depletion are considered as "source constraints", while climate change is a "sink constraint"

fuel substitution and technology. The output is a rather detailed picture of how energy demand, fuel costs and competing supply technologies could develop over time in various regions.

The main exogenous inputs include GDP growth, population, technological development and resource depletion. Differently from T21, TIMER does not account for feedbacks linking the energy sector to other ones. Though the uncertainties involved in these feedbacks may be large, the lack of interrelations between different sectors is an important limitation that is not addressed with optimization or econometric models, which is why the author attempts at proposing a more comprehensive approach to energy issues.

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on the energy-economy system.

4. Research Tools and Analysis

4.1 Introduction

This research effort investigates to what extent energy policy formulation is context-dependent. The author aims at analyzing policy proposals intended to resolve energy issues at the global, regional and national level. An integrated framework representing society, economy and environment is customized to selected countries and regions and is employed to carry out a transparent and non-partisan evaluation of the impacts of such policies on the rest of the system. Throughout this research project, the author intends to identify unintended consequences while evaluating whether optimal sectoral policies are also valid within a wider framework.

Various methodologies and models have been presented and examined as part of this research and System Dynamics was chosen to carry out the integrated analysis of energy issues hereby proposed. Threshold 21 (T21) and the Minimum Country Model (MCM), two System Dynamics models developed by the Millennium Institute, were adopted as starting frameworks and were further customized to the case studies of the Republic of Ecuador, North America and the U.S. An introduction to the methodology and an investigation of its validity is proposed in the next section of this study, and a description of the models used to carry out the research follows.

4.2 Reflections on the Validity of System Dynamics Simulation Models

Computer simulation models are supposed to be useful "playgrounds" where different policy options can be virtually tested in a simplified micro world in which time runs faster to allow users to learn from their virtual experience and reduce risk and uncertainty when dealing with the real world. The use of management "flight simulators" or "microworlds" became common practice for many private companies dealing with high degrees of detailed complexity in the past 30 years, especially encouraged by the exceptional improvement in computing technology. Nowadays, in a rapidly changing environment, where issues are arising from apparently disconnected areas and time, the importance of dynamic complexity is rapidly emerging. As a consequence, a variety of simulation tools are more frequently used and governmental agencies are considering the adoption of such tools to complement the analysis presently carried out, mainly because our mental models and understanding of systems is evolving, while their models do not, due to the limitations of the methodology used.

A parallelism in the development of simulation tools and the need for a representation of complexity can be identified. Nevertheless, from the analysis of the two periods in which this has happened (i.e. early 80s and present) significantly different characteristics emerge. In the late eighties major corporations requested technology able to deal with detailed complexity, which mainframes were eventually able to provide. In recent times, conventional tools seem to be more and more inadequate to analyze a rapidly changing environment and new tools able to represent dynamic complexity are requested. In this case though, simulation models, which should provide a simplified representation of reality, are requested to be detailed and dynamic, in other words all-inclusive. Such a need is in contrast with the definition of models, which should propose a simplified representation of reality able to provide insights about the real world. As a consequence, modelers have the responsibility to use the various methodologies available with consciousness, making sure that tools are used to analyze the issues they have been designed for.

How can validity be defined in such a context? If it is to be considered as an abstract concept, as Dreyfus claims (Dreyfus, 2001), modelers would need to

recreate reality, which is impossible, leading to the conclusions that no models are valid and insightful. If we instead define validity in relation to our objectives and what other models and techniques are already proposing, we take the conclusions of philosophers of social science as an ultimate challenge; in other words, as a statement of the goal that at last we intend to achieve.
As stated by Yaman Barlas, a well-known System Dynamicist, "*it is impossible to define an absolute notion of model validity divorced from its purpose*" (Barlas, 1996). Similarly, according to Forrester, validation can only be defined with respect to a particular situation (Forrester, 1968). These definitions imply that though nowadays we may not consider models of the early eighties as valid tools able to explain current problems, at that time they were providing the requested information, and therefore should be considered valid because they were consistent with their purpose. Nevertheless, as Barlas continues, "*Once validity is seen as "usefulness with respect to some purpose", then this naturally becomes part of a larger question, which involves the "usefulness of the purpose" itself. Thus, in reality, judging the validity of a model ultimately involves judging the validity of its purpose too, which is essentially non-technical, informal, qualitative process*" (Barlas, 1996; a very similar concept can be found in Shreckengost, 1996; Forrester, 1996; Rouse, 1985). On top of that, concerning policy-oriented models, Forrester and Senge (1980) state that "*the ultimate objective of validation in system dynamics is transferred confidence in a model's soundness and usefulness as a policy tool*" (Forrester and Senge, 1980).

For the purpose of this study, particular attention is given to System Dynamics during the analysis of the validity of models and methodologies. Barlas distinguishes between models that are "causal-descriptive", because they identify causal relations and describe the structure and functioning of a system, and those that are "correlational" (Barlas, 1996). The latter category is commonly based on optimization and econometrics, where historical data are used to define the structure of the model and its validity is defined based on the accuracy in which such models can replicate historical data, not on the validity of the structure itself (e.g. equations). This type of validation is challenged by parametric uncertainty, which, when analyzing complex problems, is not trivial and still very relevant (Kelly and Kolstad, 1998). In other words, it can be said that every model of this kind is as good as its assumptions.

Validation of causal-descriptive models, such as System Dynamics ones, goes beyond the analysis of inputs and outputs and includes an in depth scrutiny of the structure of the model. Since such tools aim at representing the functioning mechanisms of the system through the identification of causal relations, they define a theory of how the system works. This theory has to be validated, and this is why it is often said that "*a system dynamics model must generate the right output behavior for the right reasons*" (Barlas, 1996). In other words, this means that the validation of a System Dynamics model includes an analysis of the coherence of structure and purpose, as well as the verification of the technical soundness of the equations (Coyle and Exelby, 2000).

The following sections of the study aim at researching the extent to which System Dynamics computer simulation models relate to the main currents of thought on Artificial Intelligence and computer simulation in the philosophy of social science. This study focuses on Integrated Assessment Models, such as T21 and MCM, with integrated energy models -tools designed to support policy formulation and evaluation. T21 is largely based on System Dynamics, accounts both for detailed and dynamic complexity and generates future projections by accounting for cross sectoral interdependencies that are intended to identify the context in which issues arise.

4.2.1 Questions and Concerns on Computer Simulation Models

A computer simulation model is a computer program, or network of computers, that attempts to simulate an abstract model of a particular system (Strogatz, 2007). More in details, a model can be defined as a representation of a physical system that in some way simulates the behavior of the system, may consist of a computer program and may analyze a problem, increase understanding of the system, forecast future states of that system, or predict the outcomes of measures taken to change the system (Karas, 2004).

Models have become useful mathematical tools for the analysis of many natural systems, with the objective to gain insight into the operation of such systems, or to observe their behavior.

In the field of Social Science, a computer simulation model can be defined as "... *a powerful new metaphor for helping us to understand many aspects of the world*", with the interesting observation that "... *it enslaves the mind that has no other metaphors and few other resources to call on*" (Weizenbaum, 1976).

Building dynamic simulation models generally implies the execution of a series of steps that include the definition of the issues to be analyzed, a background study of such issues, data collection and analysis, formulation of dynamic hypotheses, creation of a simulation model and finally validation and analysis of the results (Sterman, 2000). These steps require learning and understanding of the issues and the system in which they emerge, as well as a reduction of the complexity observed in real systems to actually create and customize a causal-descriptive simulation model.

When building dynamic simulation models aimed at producing coherent projections by understanding and representing history, two concerns emerge:

1) There is a difference between explaining and understanding the behavior of systems. While explanations can be derived from the analysis of past events, understanding presupposes a deeper investigation of the mechanisms on top of which decisions and events take place.

2) When aiming at generating and analyzing projections, there is an important limitation to be considered: models provide a prescriptive representation of the system, in which immanence (i.e. events) cannot be based on (and reduced to) history. Descriptive models are needed, as they provide insights to the functioning mechanism of the system. Furthermore, the representation of detailed complexity is not a prerequisite for the identification of events, which in fact represents a paradox for prescriptive simulation models in a way that raptures and events cannot be forecasted. The representation of dynamic complexity is a necessary condition for the identification of events and the subsequent system adaptation.

Such concerns should be addressed considering the context in which modeling takes place, where learning about complex adaptive systems happens with the aim of reducing complexity to represent the real system analyzed, and its context, in a simpler form.

4.2.2 Methodological Issues: Foundation

Learning

According to Dreyfus, explaining and understanding can be found at different levels in the learning process (Dreyfus, 2001). Dreyfus identifies seven stages of learning. While the capability of properly explaining why certain events took place (ex-post), can be associated to Proficiency and Expertise, understanding the issues and the processes that generate them should be coupled with Mastery. In this analysis an event is to be considered as Badiou's "*immanent break with a given situation*", where a situation is a singular configuration, an "infinite multiple" which can be "politico-historical" or "strictly physical or material" for instance (Badiou, 2000). An event, as infinite multiple, can be coupled with chaos theory and the Lorenz Attractor, where a small set of interconnected equations, creating a high degree of dynamic complexity, can lead to unforeseeable behavior (Lorenz, 1963).

Proficiency, stage 4 in the learning process, according to Dreyfus identifies students who have made “situational discrimination” and are able to analyze the situation to identify problems that need to be solved. At this stage of the learning process the answer cannot be identified easily and the approach also requires some investigation. According to Dreyfus, being able to recognize and identify issues means also having the capability to clearly and coherently describe such problems and systems, which he identifies as “intuitive reaction” (Dreyfus, 2001). Similarly, the first step of the modeling process with System Dynamics consists in identifying the key issues to be solved (Randers, 1980). Modelers therefore have to be able to analyze the system, identify issues and find their causes and impacts. The latter step requires further research for novice modelers, which have to study the “history” of the system, while it is a straightforward step for expert practitioners. Dreyfus describes such skills in the stage 5 of the learning process, Expertise.

Expert students and modelers can clearly identify what methods and approaches have to be used to find solutions to the issues being investigated. They can do so thanks to their vast experience in discriminating situations. Modelers, more specifically, when identifying dynamic hypotheses -the second step of the modeling process (i.e. defining dynamic hypotheses (Randers, 1980; Sterman, 2000)- are advised to draw causal maps of the systems analyzed. Such diagrams are very much based on personal experience and are usually created instantaneously based on already existing work. As Dreyfus states, this level of learning “*allows the immediate intuitive situational response that is characteristic of expertise*” (Dreyfus, 2001). Similarly, in System Dynamics two main feedback loops can be identified to define all types of behavior in real systems: reinforcing and balancing (Forrester, 1961).

The following stage of learning, stage 6, is called "mastery" by Dreyfus and can be considered as the threshold between the ability of explaining and understanding. In fact, mastery involves developing a personal style, which can be easily applied to modeling too, where a variety of models of different styles can be created and still lead to similar analyses and conclusions.
Such level of experience can be reached in different ways, through experience or through training with a number of different masters. The latter example is used by Dreyfus to define mastery: "*Working with several masters destabilizes and confuses the apprentice so that he can no longer simply copy any one master's style and so is forced to begin to develop a style of his own. In so doing he achieves the highest level of skill. Let us call it mastery*" (Dreyfus, 2001).

Using Badiou's definition of event and Dreyfus' classification of learning, immanence results to be the ultimate challenge for modelers. As a matter of fact, if the modeling process is a learning journey in itself (Sterman, 2000), and if expert practitioners gather their knowledge from experience (Dreyfus, 2001), they will never be able to identify immanence, a singular and unique configuration (Badiou, 2000), before an event actually takes place, unless the models they build are dynamically representing the underlying causal structure of the system and allow for emergent behavior (through shifts in loop dominance). Modelers, therefore, attempt to represent something (e.g. events) that cannot be clearly identified before its manifestation (SD contributes to this effort, providing a descriptive framework). This constitutes a dilemma that modelers working with prescriptive tools have to face, represented by the impossibility to represent immanence through experience. As mentioned above, when dealing with descriptive models such dilemma can be solved by learning about and representing what the main forces driving the behavior of the system are.
A longer term focus then helps see the events that led the system to change and to the identification of those structural components that may generate new ones in the

future (e.g. through a shift in trends and strength of selected feedback loops). The energy models proposed in this study, integrated into T21 and MCM, account for long time frames to test the results of the simulation against history and project into the future long enough for longer term trends to emerge.

Explaining and Understanding

Many similarities can be found with the processes modelers of different disciplines use to create their frameworks of analysis: when studying historical events, both proficient and expert practitioners would use their own knowledge and experience to define, ex-post, a framework that allowed events to take place or that would be able to reproduce them. Such representation is usually subjective for what concerns the identification of the main drivers of the system's behavior, but it is still very much related to previous existing work.

At the Mastery level, in the System Dynamics field, it is commonly said that an infinite number of different models can be built to analyze the same issue and still lead to very similar results (Sterman, 2000; Shreckengost, 1996; Forrester, 1996; Rouse, 1985). This implies that the understanding of objective mechanisms is in place and those personal unique styles and techniques are being used. This is consistent with relativistic, holistic and pragmatist philosophies. In fact they say that "*No particular representation is superior to others in any absolute sense, although one could prove to be more effective. No model can claim absolute objectivity, for every model carries in it the modeler's worldview. Models are not true or false, but lie on a continuum of usefulness*" (Barlas and Carpenter 1990).

A possible, though controversial, way of explaining (not understanding) why events took place, consists in a description of which happenings led to their creation (happenings are considered to be prerequisites for events to take place according to Davidson (Davidson, 1980)). This means abstracting and objectifying the object of analysis, typical of the first stages of learning, where a filter is applied based on personal judgment and experience. Such process of objectification increases the validity of a model according to the reductionist/logica1 positivist school. They state that a valid and valuable model is simply a correct objective representation of reality. In this philosophy, which provides a concept of validity closer to "correlational" models, the validity of a tool has to do with the accuracy of the results and not with the actual usefulness of the model itself (Barlas and Carpenter 1990).

Understanding why events emerged implies instead more than the accurate representation of reality. In fact, it requires the identification of the underlying structure of the system analyzed, which accounts for causal relations, non-linearity and feedback loops. Understanding, in fact, can be defined as "*a psychological process related to an abstract or physical object, such as, person, situation, or message whereby one is able to think about it and use concepts to deal adequately with that object.*" Understanding also implies the existence of a real world relation to those subjects or agents that allows decisions and thoughts to be correctly interpreted and dealt with (Skjervheim, 1996).

With such definition, understanding is highly connected to conceptualization, in a way that in order to understand a phenomena it is necessary to have it conceptualized, but also to have had a real personal, subjective, relation with the subject. Similarly, modeling consists in conceptualizing reality to a simplified form with the aim to identify what decision rules or options are made available to agents acting within the system. Computer simulation models with a prescriptive structure, which does not allow for emergence, will always be limited to the research of an objective set of decision rules or options (i.e. objective function), while descriptive models can reach higher levels of understanding through an investigation and a representation of the underlying causal structure of the real world. The limitation faced by prescriptive models represents a second dilemma for these tools, in the fact that conceptualization to reduce world's complexity requires objectification with such methodology. It is therefore clear that, in order to represent emergent behavior, models should be able to incorporate structural components that are not based on objective rules only. This is consistent with the fact that it is impossible to define a formal or objective process of "theory confirmation" (Barlas, 1996). For this reason, it is not possible to expect that a validation process in the social sciences can be exclusively formal and objective (Barlas and Carpenter 1990).

When modeling, practitioners investigate what the underlying structure of a system is, being open to gather information and trying to identify what mechanisms drive the observed behavior independently from what they might be. Identifying these mechanisms means identifying a set of causal relations existing within the system, so that understanding can be reconducted to the explanation of what relations and interdependences generated the event being investigated, with limitations related to experience and objectification, and with a specific time frame (history).

This recalls the thoughts of Rostislav Persion: "*the process of introverted thinking (Ti) is thought to represent understanding through cause and effect relationships or correlations. One can construct a model of a system by observing correlations between all the relevant properties. This allows the person to generate truths about the system and then to apply the model to demonstrate his or her understanding*" (Persion, 2008). In the System Dynamics context, the identification of causal relations originates from the identification of correlations (through simulation) as an output of the model, which allows overcoming major challenges, such as objectification and oversimplification. Conventional econometric and linear programming models, which base their analysis on correlation, are limited to explanation (not understanding) of phenomena especially when dealing with the creation of future projections (this does not exclude that modelers can understand the system thanks to their knowledge and dynamic mental models). With such methodologies historical data are analyzed, relevant data series are selected and then used to obtain projections. With such a heavily dependence on historical data, this type of models loses confidence when new and unexpected events happen. This is due to the fact that they are unable to provide insights to the mechanisms driving un-experienced changes in the system and only use historical trends to extract projections. In System Dynamics simulation models such as T21, understanding the processes that generate changes in the systems analyzed is the key objective of the modeling process. The structural foundation of the methodology lies in fact in the analysis of historical events that change the behavior of the systems to discern what the causes and effect of change were. SD models aim at representing the key causal relations underlying the system analyzed, leading to a deeper (though not full) understanding of the system itself and its mechanism.

Analyzing Issues Arising in Complex Adaptive Systems

Conceptualizing and defining understanding in the context of modeling is particularly relevant when considering that the object of investigation are complex adaptive systems, subject to continuous and often sudden change. Complex adaptive systems denote systems that have some or all of the following attributes (Johnson and Neil, 2007):

- The number of parts (and types of parts) in the system and the number of relations between the parts is non-trivial – however, there is no general rule to separate "trivial" from "non-trivial;"

- The system has memory or includes feedback;

- The system can adapt itself according to its history or feedback;

- The relations between the system and its environment are non-trivial or non-linear; and

- The system can be influenced by, or can adapt itself to, its environment.

A complex adaptive system, like any social system, is therefore characterized by feedback, delays and non-linearity, three crucial elements that define it dynamic behavior and complexity. Any complex adaptive system is also context dependent and is a learning environment where historic memory can influence the future development of the system itself (Holland, 1995).
When accepting such definition becomes more evident that the System Dynamics methodology accounts for the characteristics required for the analysis of complex adaptive systems. The representation of feedback (to account for embedded memory), delays (adaptation may occur in relation to history) and non-linearity (to represent non-trivial and at times counter intuitive relations within the system), contribute to the representation of the context, which can influence the future evolution of the system. Nevertheless, the system is in continuous evolution and both the identification of parts and relations is non-trivial.
When considering future projections and dealing with complex adaptive systems, in addition to the challenges in defining a structure for the system analyzed, the use of analogy (based on experience) can provide insights on future developments of similar issues in non-dissimilar contexts. On the other hand, the creation of an event would immediately produce new structures and modify the strengths of factors influencing the system or the agents forming it. This represents a challenge, if not a dilemma, for the creation of computer simulation models. Deep understanding is therefore required also to comprehend to what extent the system changes and evolves after events (natural or induced, emergent or expected) take place.

Examples of complex adaptive systems include any human social group-based endeavor in a cultural and social system such as political parties or communities. John H. Holland defines a Complex Adaptive System (CAS) as follows: "*(CAS) is a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to* *what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents*" (Holland, 1992; Waldrop, 1992).

4.2.3 Methodological Issues: Application

Phenomenology

The ultimate objective of modelers is to understand systems. In order to do so they analyze such system and build a computer simulation model potentially able to provide insights on events and phenomena through the identification of the underlying structure that allows for their creation. This process presents many similarities with Edmund Husserl's definition of phenomenology: (Phenomenology is) "*the reflective study of the essence of consciousness as experienced from the first-person point of view*" (Smith, David Woodruff, 2007). Phenomenology examines phenomena to understand and extract from it the main characteristics of related experiences. The System Dynamics modeling process does present similarities with this definition: its aim is to represent the underlying structure of systems, which is able to explain the mechanisms that allowed events to take place or that will do so in the future under specific and well defined conditions (Sterman, 2000).

When looking at the modeling process, and more specifically at the identification of structural drivers of behavior in a well defined system, phenomenology suggests that modelers can only identify causes after an event has taken place, while it is significantly more challenging to do so (if not impossible) in order to forecast happenings and events. This is particularly confirmed by the first and third dilemmas identified earlier, respectively the singular and unpredictable nature of immanence and the continue evolvement of systems.

Such dilemmas pose a major challenge to the validity of simulation models, indicating that a good part of the exercise of modeling would be in fact speculation based on an incomplete understanding of the system, a conclusion drawn based on the second dilemma. In other words a model could be used to simply simulate a variety of assumptions, as scenarios in fact, that would greatly influence its outputs and would actually represent no more than "educated guesses". To counter this problem, with Threshold 21, while recognizing the limitations of the methodology, the author selected a longer time frame to carry out an analysis of the past and most likely future causal relations affecting the system, to then proceed with the definition of the boundaries of the model, that is the identification of causal relations that determined a shift in the behavior of the system (or that might indicate one in the future). Though this process does not guarantee confidence in the results of the simulation, it indicates that an analysis of the major forces driving the system has been carried out with the aim to identify the main causes and effects that future exogenously simulated events (e.g. policy implementation) may generate in the system. This, in fact, represents an extension of the more simplistic (but not of easier execution) analysis of historical data to then select relevant data series and extract projections from longer-term historical trends.

Modeling Complexity

In order to gain insights on real complex adaptive systems, modelers aim at creating a reliable and valid model representing a simplified version of real systems. This way the complexity is reduced to the most important causal relations and feedback loops that already did (or might) influence the behavior of the systems being analyzed.

The definition of complexity is similar to the one of complex adaptive systems. Complexity is characterized by a number of factors (or elements) in a system, which are interconnected with each other (or depend on each other). From a different point of view, it could be said that complexity emerges from the interaction of various connected and apparently non connected factors (Waldrop, 1992).

Weaver defines the complexity of a particular system as "*the degree of difficulty in predicting the properties of the system if the properties of the system's parts are given*" (Weaver, 1948). In Weaver's view, complexity comes in two forms: disorganized complexity, and organized complexity (Weaver, 1948). Interestingly, also in the field of System Dynamics two types of complexity are identified: detailed and dynamic (Sterman, 2000). While the detailed complexity is characterized by a large number of linear relations, the dynamic components imply the existence cross-sectoral connections characterized by non-linearity and delays. Weaver draws a very similar distinction between organized and disorganized complexity. Organized complexity emerges from well defined relationships within the system or across systems (e.g. the level of details embedded in the system, correspondent to detailed complexity). Disorganized complexity instead results from the size of the system, the large amount of parts that forms it and the connections existing among them. In this case, the interactions of the parts can be seen as largely random (correspondent to dynamic complexity in System Dynamics) and the behavior of the system can be explained by using probability and correlation. A fundamental characteristic of disorganized complexity is that the aggregated behavior of the system shows properties not resulting from the mere sum of its components.

An example of detailed and organized complexity is the representation of the steps of energy conversion processes from primary sources to end use fuels. Every single step can be identified, measured and defined even if the process accounts for thousand of steps. Dynamic and disorganized complexity can be identified in the definition of the price of such energy sources as well as in social systems, where the individual responses to price change do not necessarily provides insights on the aggregated behavior of the system.

As all frameworks, System Dynamics simulation models represent a simplification of a reality that is complex, dynamic and unpredictable. The complexity of the real world is limitless and reducing it to analyze specific issues is not always a straight forward exercise. This reflection stems from the fact that complexity always exists and reducing it to a limited number of factors may actually lead to erroneous analyses, especially in the case of dynamic and non organized complexity. One of the risks to be acknowledged is that, as Michael Behe states, irreducible complexity can be found in a "*single system which is composed of several interacting parts that contribute to the basic function, and where the removal of any one of the parts causes the system to effectively cease functioning*" (Behe, 1996). Although Behe's definition refers to the field of biology, creating a simplified representation of reality as a basis for the construction of a computer simulation model, by selecting the major factors influencing the behavior of such system, may not allow for a correct representation of the system itself because some relevant elements defining the system's functioning will be excluded from the analysis. On the other hand, it has to be noted that representing all factors would mean reproducing reality with all its complexity. This is a fundamentally important step in the definition of the structure of the model that should be taken into consideration when defining its boundaries, and when evaluating its validity.

4.2.4 Critics to Artificial Intelligence

Learning from and about real phenomena as well as attempting to identify optimal ways to reduce complexity, do not solve all the problems related to customization and use of computer simulation models. Dreyfus raises relevant concerns on the validity of such methodologies and how they are applied (Dreyfus, 1979), which can be used to summarized the challenges identified so far. Firstly, Dreyfus critiques what he calls a psychological and epistemological assumption of Artificial Intelligence (AI), which consists in the fact that the mind works by performing discrete computations (in the form of algorithmic rules) on discrete representations or symbols. This assumption reflects, in fact, how dynamic computer simulation models work. They do run on discrete computations on a closed algebraic system. Dreyfus arguments also that experts do not follow or create rules, they simply use examples to explain what their main skills or applied processes are (Dreyfus, Dreyfus, 1986). This indicates that computer simulation models, when working with rules and discrete algebraic equations, can never be very accurate in replicating or forecasting events because they do not take place based on formal rules. In other words, the emerging characteristics of systems cannot be captured or forecasted by models.

A second assumption criticized by Dreyfus, the ontological one, presupposes that reality consists entirely of a set of mutually independent, atomic (indivisible) facts. Accepting such assumption would mean that human behavior is, to a large extent, context free because all parts of the system can be isolated and analyzed separately according to specific laws, such as in physics. In epistemology, contextualism is the treatment of the word 'knows' as context-sensitive. Context-sensitive expressions are ones that "*express different propositions relative to different contexts of use*" (Stanley, Jason, 2005). Dreyfus strongly denies such assumption and argues that we cannot (and never will) understand our own behavior by considering ourselves as things whose behavior can be predicted via “objective”, context free scientific laws. According to Dreyfus, a context free psychology is a contradiction in terms (Dreyfus, Dreyfus, 1986).

System dynamics modelers recognize the importance of feedback and cross-sectoral relations and do create a simplified model of reality in which the causes of phenomena are broken down to better understand the origin of such events. While this process is in contrast with Dreyfus’ assertion that reality is indivisible, it does identify and represent some of the relations existing among various parts of the system. By doing so, System Dynamics models, such as T21, though using a closed descriptive structure, do take into account and represent the context that characterizes the system analyzed (this is mainly done by incorporating social, economic and environmental factors in a single comprehensive framework).

Acknowledging the limitations posed by computer simulation models, an analysis of the modeling process is carried out to identify eventual strengths that might help further developing the studies currently carried out to reduce the gap that Dreyfus identifies.
According to anthropology, more precisely ethnography, social phenomena take place thanks to a structure based on processes, which generate happenings (Davidson, 1980). These happenings at times turn into events, which are constructed by processes and determined by cultural factors or unique contexts (Davidson, 1980). Similarly, a dynamic simulation model is built upon a structure of differential equations, each of which can be seen as a process. Furthermore, the model generates simulated behavior, which corresponds to happenings. Events are represented by shifts in dominance that eventually help identifying tipping points. According to ethnography, in fact, emerging events strongly influence the structure of the system that generated them, which is evolving over time. In all computer simulation tools the structure of the model, hard wired into equations, cannot modify itself (i.e. new equations cannot be created by the software based on the results of the simulation), excluding from the analysis the study of raptures and elements of discontinuity. On the other hand, System Dynamics simulation models allow for changes in the strength of the structural causal relationships identified, creating a link between structure and behavior. According to Dreyfus, a system can never close up in a defined structure because unpredicted emergent behavior would change its structure and further evolve. The

representation of systems and their complexity with System Dynamics models proves the opposite.
In the case of Threshold 21 wide boundaries are utilized to represent what are considered to be the main factors that did influence the system in the past and that might influence it in the future. These include some relations that may not be relevant at present state but may become determinant in the future, or other that were responsible for changes at different past times. Though a closed-loop representation may seem to limit the detailed analysis of complex issues, it provides value added in improving the understanding of the system, both structure and behavior. System Dynamics models allow for a more holistic representation of the issues analyzed by adding their context (e.g. socio-economic and environmental dimensions) and crucial functioning mechanisms to the structure of the model.

4.2.5 Conclusions

The impossibility to identify and represent events and emergent characteristics of the system analyzed has posed serious questions about the validity of computer simulation models aimed at projecting future events. A natural conclusion to this analysis would suggest that if factors that have profoundly changed our social, economic and environmental systems in the past, such as raptures and discontinuities, cannot be identified nor represented, the creation of forward looking scenarios may be considered a mere speculative exercise (i.e. educated guesses) providing little insights. Furthermore, prescriptive simulation tools are only based on past experience and incorporate potentially biased assumptions derived by the knowledge of the researchers who created them, especially if they have not reached the "mastery" stage of learning. Since society is in continuous evolution, the creation of prescriptive models couldn't 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.

The following four major dilemmas summarize the main challenges mentioned above:

1. Immanence cannot be identified only through experience, neither at the highest levels of learning (i.e. Mastery);
2. It is not possible to reach full understanding through conceptualization aimed at finding objective rules (e.g. modeling);
3. Social systems continuously change, therefore understating is a continuous, never ending process;
4. Reducing limitless complexity is not always viable and limits the validity of the analysis being carried out.

Given the above, a modeler's job resembles a journey searching for knowledge and a level of understanding that cannot ultimately be found with the tools he owns. As models are never perfect, modelers will never be fully satisfied with their work and will keep striving to improve it and make it more useful. The amount of information and understanding they will gather and accumulate through this journey will eventually allow them to reach the mastery level of learning, when they will properly interpret and conceptualize current and past events, still leaving the projection of future events largely unknown. A significant advantage gained in such process reside 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 System Dynamics simulation models, such as T21 and MCM, the challenges mentioned above seem achievable given that:

1) The identification of causal relations allows for 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. System dynamics allows representing complexity through a descriptive, not prescriptive model;
3) Behavioral change is continuous, while structural change can be infrequently observed. System Dynamics focuses 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 System Dynamics model therefore results to be a gradual, semiformal and conversational process (Barlas, 1996), 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, System Dynamics tools and T21 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 (Barlas, 1996). 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*" (Barlas, 1996).

When using System Dynamics and descriptive modeling tools the role of modelers aiming at providing insights on policy formulation and implementation should consists in (providing) "... *tools that exploit new ways to encode and use knowledge to solve problems, not to duplicate intelligent human behavior in all its aspects*" (Duda, Shortliffe, 1983).

System Dynamics models in fact can 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 (DeGeus, 1992; Morecroft, 1992). Dynamic simulation models should therefore be seen as learning tools on which to base a constructive dialogue to reach better decisions in an objective environment where various assumptions and the manifestation of events can be tested and where the audience can be abstracted from fully subjective positions. Dynamic simulation models are by no means perfect and will never be; nevertheless, we have the responsibility to use our best scientific understanding to develop reasonable and sustainable policies. Integrated models allow us to do so by enhancing the understanding of systems and providing useful insights to be shared with stakeholders.

4.3 T21, MCM and Integrated Energy Models

To carry out the research hereby presented, the author has employed System Dynamics and developed customized applications of the Threshold 21 model (North America, USA) and Minimum Country Model -a reduced form of T21- (Ecuador). In addition, new energy modules for these models have been created to analyze more in detail energy intensive industries and the U.S. transportation sector (i.e. urban and freight rail). Though the energy modules developed differ from EIA's NEMS (EIA, 2003), IEA's WEM (IEA, 2004) and IIASA's MESSAGE (IIASA, 2001 and 2002) in the level of detail represented, their offer higher dynamic complexity and a more coherent representation of interconnected sectors such as energy and economy as well as society and the environment.

Threshold 21 (T21) (Millennium Institute, 2005) and the Minimum Country Model (MCM) (Pedercini et al., 2008) are System Dynamics based models developed by the Millennium Institute, a non-for profit based in Arlington, VA, USA. These models allow for the representation of feedbacks, delays and nonlinearity and are designed to support national development planning. Both are computer-based national development planning models consisting of a set of dynamically integrated sectors that together would be adequate to represent the long term development of most countries, industrialized and developing (Millennium Institute, 2005). These models were conceptualized and further improved by reviewing the literature on tools for planning national development, which resulted in the publication of a book cataloging about fifty of the most interesting and useful models identified (Barney, 1991).

The Millennium Institute (MI), in the person of, among others, Dr. Qu and Dott. Pedercini, has developed T21 over the last 15 years after a first version of the model was donated to MI by Dr. Eberlein of Ventana Systems, Harvard, MA. Dott. Perdercini created the Minimum Country Model in 2004, as a reduced form of T21 that would be better suited for a simplified analysis of the main drivers of national development as well as for training courses and capacity building in developing countries.

The purpose of creating the models used in this study is to understand energy issues and to show how those issues are context dependent and relate to society, the economy, and the environment. Understanding the short- and long-term impact of energy issues in a far-reaching and integrated way is fundamental to testing and planning sustainable, effective, and result oriented policies in our complex environment.

The value added provided by this study consists in the creation of energy models that account for a variety of energy-related feedback loops that are missing in T21 and MCM. When incorporating these energy models, which become modules of

T21 and MCM, users and policy makers can recognize the value of the interdependencies existing between energy and society, economy and environment by using a set of Integrated Energy Models. These models are highly customized and tailored around a specific set of issues and geographical context. The incorporation into T21 and MCM allows for the representation of the context in which energy issues arise, providing insights on whether side effects or elements of policy resistance may arise in the medium and longer term.

The main research questions to be answered with these models are the following:

Structural Analysis

- What are the critical relations within and across sectors that need to be incorporated into a comprehensive dynamic model to appropriately represent what happens in the real world?
- What are the essential sets of data and parameters needed to define the relationships and validate the model?

Scenario Analysis

- What are the likely results of continuing the current social, economic, and environmental policies on the availability and use of conventional energy sources?
- What is the set of likely scenarios that will help us foresee our national and global energy future (e.g. crude oil availability, technology development)?

Policy Analysis

- How will currently discussed energy policies (e.g. cap-and-trade) help the transition to dealing with scarcer conventional energy sources, and how much exogenous political action is needed to achieve a sustainable transition?

- What interventions are needed to allow renewable energy resources to ease the transition to a less polluting economy (e.g. what is the potential for the implementation of wind, solar, and bio energy both in terms of technology and sustainability)?
- What mitigating measures are needed to help offset the possible negative results of the desirable policy options?

Based on these research questions, the author aims at analyzing the following energy-related issues: energy availability for current and future generations, future changes in fossil fuel prices and reaction of demand, effective transition to less dependence on fossil fuels (particularly oil), impacts of fast growing countries on energy availability and energy security, reduction of greenhouse gases (GHG) and carbon emissions to reduce the treat of climate change, measures to mitigate the negative effects of the energy transition and of the inevitable changes in climate.

Since the models proposed share a common underlying structure, but are further highly customized, the following section provides an overview of their purpose and structure. T21 and MCM are introduced to highlight the characteristics of the social, economic and environmental spheres; instead, the presentation of the energy models will focus on the original contribution of this study and on the characteristics of the different energy contexts analyzed. More details on the structure of the models are available in Appendix C.

4.3.1 Threshold 21 (T21) and the Minimum Country Model (MCM)

Both T21 and MCM are structured to analyze medium-long term development issues at the regional and national level. These models integrate the economic, social, and environmental aspects of development planning in a single framework. T21 and MCM are created to complement budgetary models and short-medium term planning tools by providing a comprehensive and long term perspective on development (Millennium Institute, 2005).

These tools support policy planning in various ways, both by highlighting key development issues in the baseline scenario, and by projecting different policy choices and scenarios in alternative simulations. These results provide a good basis for the creation of dialogue and for further defining chosen policy actions, as well as for monitoring and evaluation of their performance.

The main characteristics of T21 and MCM include (Millennium Institute, 2005):

a) Integration of economic, social, and environmental factors;
b) Representation of important elements of complexity – feedback relationships, non-linearity and time delays;
c) Transparency in the structure, assumptions, equations, and data requirement;
d) Flexibility in creating customized versions of countries based on country-specific conditions;
e) Simulation of the short- and long-term consequences of alternative policies; and
f) Provision of comparison to reference scenarios and supports advanced analytical methods, such as sensitivity analysis and optimization.

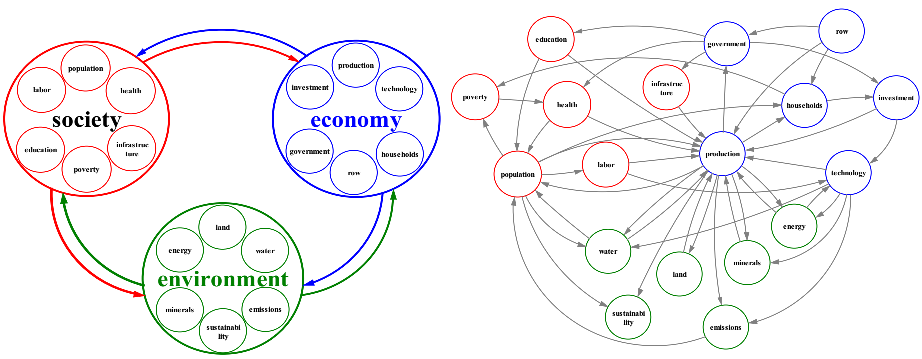
These models provide policymakers and other users with an estimation of the impacts of the implementation of different policy choices on a variety of sectors, both social, economic and environmental. In addition, T21 and MCM allow for the simulation of scenarios based on assumptions proposed by different agencies and organizations. In other words, these models represent the common basis on which divergent ideas and assumptions can be simulated to create a dialogue among parties. This is done through the explicit representation of feedbacks among economy, society, which are important components to identify paths for sustainable development.

Structure[5]

T21 and MCM are built around a core structure that broadly reflects the structure and relations of the social, economic and environmental sector, which are called spheres in the model. These models are highly flexible and are customized to a specific set of issues for a given geographical area. Within each major sphere are the sectors, modules, and structural relations that interact with each other and with factors in the other spheres.

The figure below represents a conceptual overview of T21, with the linkages among the economic, social, and environmental spheres.

Figure 2: Conceptual overview of T21



The Social sphere of T21 contains detailed population dynamics organized by sex and age cohort, health (identified by the proxy "life expectancy"), education and other sectors (see table 1). While T21 accounts for 13 modules in the social sphere, MCM includes only four: population, education, health care and roads. The Economy sphere of the models contains disaggregated major production sectors for T21 (agriculture, industry and services) and a single aggregated module for MCM. In both cases the calculation of production is characterized by Cobb-Douglas production functions with inputs of resources, labor, capital, and

[5] For a model detailed description of the structure of the models see: Millennium Institute (2005). Threshold 21 (T21) Overview. Arlington, VA.; Pedercini, M., B. Kopainsky, P. I. Davidsen, S. M. Alessi (2008). Blending planning and learning for national development.

technology. A Social Accounting Matrix (SAM) (Drud et al., 1986) and a System of National Accounts (SNA) (IMF, 2008) are used to elaborate the economic flows and balance supply and demand in each of the sectors. Standard IMF budget categories are employed, and key macro balances are incorporated into the models (IMF, 2001).

The Environment sphere tracks land allocation (i.e. urban, agricultural, fallow, forest, and desert), water and energy demand in MCM. T21 accounts also for energy supply and fossil fuel production, air emissions (CO_2, CH_4, N_2O, SO_X and greenhouse gas) and the calculation of the ecological footprint.

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	

Table 2: Modules, Sectors and Spheres of MCM-Starting Framework.

SOCIETY	ECONOMY	ENVIRONMENT
Population Sector:	**Production Sector:**	**Land Sector:**
1. Population	5. Firms	9. Land
Education Sector:	**Households Sector:**	**Water Sector:**

2. Education	6. Households accounts	10. Water demand and supply
Health Sector:	**Government Sector:**	**Energy Sector:**
3. Access to basic health care	7. Government accounts	11. Energy demand and supply
Infrastructure Sector:	**Banks Sector:**	**Emissions Sector:**
4. Roads	8. Banks	12. Air Emissions

Feedbacks

The major feedback loops underlying society, economy, environment, and energy include population and income (involving economic and social spheres); labor availability (involving economic and social spheres); public and private economy (involving the economic, environmental, and energy spheres); resources and environment (involving social, economic, environmental, and energy spheres). The major feedback loops underlying society, economy, environment, and energy follow:

- Public economy (involving the economic sphere);
- Private economy (involving the economic sphere);
- Resources and environment (involving economic and environmental spheres);
- Labor availability (involving economic and social spheres)
- Population and income (involving economic and social spheres)

Energy Modules

Given the focus and research questions of this study, a deeper analysis of the energy modules included in T21 and MCM is advised.

T21 accounts for energy demand, supply –including fossil fuels production- and emissions.

The major drivers of national energy demand in the medium-long term are tracked in the T21 Energy Demand module. Energy demand is calculated using GDP, energy prices and technology (i.e. energy efficiency) and the energy sources considered are electricity and non-electricity. While GDP and technology are

endogenously calculated in T21, energy prices are exogenous, which is a reasonable assumption for countries that have little impact on the global energy market and where domestic energy prices are heavily dependent on world prices. Energy supply accounts for fossil fuel production, nuclear, hydro and renewable energy generation. Fossil fuel production, which is based on the explicit representation of stocks and flows for discovery and recovery processes, is mostly exogenous (apart from the use of industrial technology in computing the extent to which exogenous discovery and recovery fractions improve over time). Electricity generation is calculated using exogenous nuclear, hydro and renewable energy (as they are characterized by large capital investments and usually represent policy variables influenced by national energy policies) and endogenous fossil fuel consumption. The penetration rate of fossil fuels for electricity generation is defined by using exogenous fossil fuel prices and exogenous efficiency conversion parameters.
T21 calculates energy and fossil fuel dependency and assumes that if energy prices increase, productivity in industry, agriculture, and services will be hindered.

MCM accounts for one module representing both energy demand and supply. For simplicity, the model aggregates total energy demand and supply in one variable (expressed in Joules, BTU or barrels depending on the characteristics of the country analyzed).
Energy demand is influenced by GDP and energy efficiency, which are both endogenously calculated. The latter is calculated using relative energy prices and exogenous curves for future technology development.
Energy supply represents an aggregated fossil fuel production structure, which accounts for oil discovery and recovery, and renewable energy generation. Domestic oil price is influenced both by domestic depletion of oil and by exogenous import prices and influences investments in renewable energy, which account of a delay in building and replacing infrastructure. As for energy demand

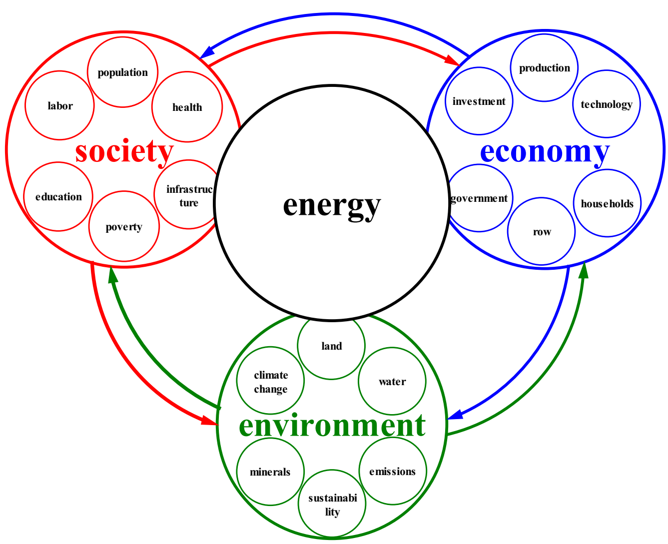
and supply, renewable energy is represented by an aggregated variable accounting for all sources that may be available in a country.

MCM also calculates air emissions, CO_2 and GHG, using energy consumption.

The contribution of this study consists in incorporating a set of more dynamic and detailed energy modules, which eventually become an additional sphere, to T21 and MCM. This extension incorporates important energy feedbacks with society, economy, and environment and allows T21 and MCM to better represent energy issues and their context in complex settings.

The main purpose for customizing these quantitative tools for integrated, comprehensive national planning is to support the overall process of strategic planning by facilitating information collection and organization, in addition to analyzing the results of alternative strategies. These models can also used as educational tools to facilitate the understanding of complex issues, thanks to their transparent and dynamic formulation.

Figure 2: Conceptual overview of T21-Ecuador, North America and USA



4.3.2 Ecuador Energy Model

The Ecuador model was created to carry out a countrywide analysis of the energy sector of the Republic of Ecuador to provide useful decision support services for climate change mitigation.

The analysis focused on investments in the power sector to mitigate the negative economic impacts of climate change, a key assumption of the Stern Review on the Economics of Climate Change (Stern, 2007). Such investment in energy efficiency and renewable energy technologies, 1% of GDP, was simulated to measure the potential to stabilize carbon emissions from fossil fuel (thermal) electric power generation. Furthermore, the customization of the model to represent the Ecuadorian context allowed for the calculation of the avoided consumer electricity costs and its contribution to poverty alleviation through, among others, job creation and improved social services.

Since the analysis is highly focused on the energy and power sectors, MCM was the initial framework chosen for the customization of the Ecuador model. MCM, with enhanced energy modules, allows for an integrated analysis of the potential impacts of investments in energy efficiency and the power sector, and the re-investment of avoided costs, on society, economy and environment, the context of Ecuador

Structure

The energy modules of the Ecuador model account for energy demand and consumption, total supply and prices. Modules used to investigate the potentially avoided electricity consumption and production capacity accompany the power sector, with electricity demand and supply, most important for the analysis proposed.

The energy sources considered in the model are oil, natural gas and electricity (which in Ecuador is generated from oil, natural gas and renewable energy sources, mainly hydro).

Energy demand is calculated for oil, natural gas and electricity. Fossil fuel demand is computed for electricity production and for direct use. The factors influencing demand for fossil fuels are GDP, energy efficiency and energy prices. Population, in addition to these factors, influences electricity demand, which is calculated for the residential, commercial, industrial and a residual "other" sectors. Consumption is assumed to equal demand, given the large availability of oil and natural gas in Ecuador.

Electricity production is calculated by accounting for demand and production capacity. Demand is calculated using retail sales and distribution, transmission and generation losses. The sum of these quantities equals gross electricity demand, from which renewable energy production is subtracted to obtain fossil fuel demand for electricity production. Demand of oil and natural gas for power generation is allocated using energy prices and efficiency. Domestic energy prices use projections for world energy prices generated endogenously by T21-USA. Energy technology addresses energy efficiency and it is calculated based on the field study carried out in the Galapagos by SolarQuest, a partner in the study. Air Pollution includes emissions (CO_2, CH_4, N_2O, SO_X, and total greenhouse gasses). Pollution is based on fossil fuel consumption.

Table 3: Modules, Sectors and Spheres of MCM-Ecuador Model.

SOCIETY	ECONOMY	ENVIRONMENT
Population Sector:	**Production Sector:**	**Land Sector:**
1. Population	6. Firms	10. Land
Education Sector:	**Households Sector:**	**Water Sector:**
2. Education	7. Households accounts	11. Water demand and supply
Health Sector:	**Government Sector:**	**Energy Sector:**
3. Access to basic health care	8. Government accounts	12. Energy prices
Infrastructure Sector:	9. Banks	13. Energy demand
4. Roads		14. Electricity demand
Labor Sector:		15. Electricity production
5. Employment		16. Energy consumption
		Emissions Sector:
		17. GHG emission, CH_4, N_2O, SO_X
		Sectors for analysis
		18. Electricity production capacity
		19. Energy demand reduction
		20. Energy conversions

Feedbacks

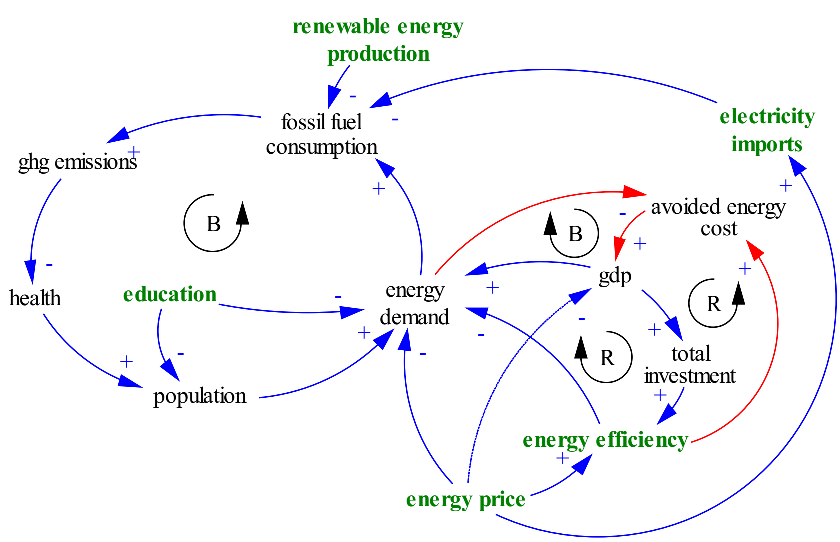
Provided that the focus of the study is the analysis of the impact of investments in energy efficiency and in the power sector, through renewable energy generation, the key variable of this study can be identified in electricity demand and use. Subsequently, air and greenhouse gas emissions should be used as metrics to evaluate the effectiveness of the investment allocated, at least in the first part of the analysis carried out.

Electricity demand is correlated, and causally linked, with population, GDP, prices and technology. Population in turns is influenced by education, which, together with increasing income, decreases fertility and population growth. On the other hand, increasing income allows for better health treatments, increasing life expectancy, which is susceptible to air emissions. Education, in addition, tends to decrease energy demand by influencing behavioral change in the form of conservation.

Increasing energy prices and improving technology (i.e. energy efficiency) also decrease energy demand. Under certain circumstances though, increasing energy efficiency frees up resources to households and business, and the resulting reduction in energy consumption may be lower than expected. In fact, the avoided costs can be spent or reinvested, generating a positive effect on GDP, which in turn increases energy demand. The avoided cost though, can be further reinvested in energy efficiency and in social services, to improve education and health offerings as well as infrastructure.

Expanding the boundaries of the model, from an energy tool to an integrated model for supporting policy formulation and evaluation, allows to appreciate the impacts of sectoral energy policies on society, economy and environment while identifying eventual synergies or elements of policy resistance.

Figure 3: T21-Ecuador, causal loop diagram representing the linkages between the power sector and the rest of the model.



4.3.3 North America and USA Energy Models

The USA model was firstly developed as part of the author's previous research, to inform the U.S. policy debate by generating forward looking scenarios that would take into account feedbacks, delays and nonlinearity characterizing the U.S. energy and economic landscape (see Bassi, 2008). Subsequently the model was improved to fully represent the upcoming energy transitions and was used to support policy formulation and evaluation in collaboration with Hon. Rep. Roscoe Bartlett, U.S. Congress.

The North America model is the result of additions and further improvements made to the USA model. The Association for the Studies on Peak Oil and Gas (ASPO-USA) has supported the research and embracing the addition of geographical areas and scenarios that were not considered in the U.S. study. The North America energy model aims at analyzing various energy-related issues including the socio-economical consequences of an early petroleum production peak and the decreasing energy return on investment (EROI) of fossil fuels, which is the energy returned from an activity compared to the energy invested in that process (Odum, 1971; Hall et al., 1986; Cleveland et al., 1984; Cleveland and Kaufmann, 2001). The model is intended to generate scenarios and simulate currently discussed policies that show the results across all the key indicators for the economy, society, and environment. With this tool, users and policy makers can access information on the broader medium to longer term impacts of scenarios on energy availability and proposed policies aimed at reducing consumption (i.e. CAFE) and varying the energy supply mix (i.e. RPS).

While the North America model mainly focuses on the integrated analysis of the impacts of liquid fuels shortages and on subsequent trade issues between U.S., Canada and Mexico, the USA model aims at analyzing the impact of some of the policy proposals that have been recently elaborated and proposed by the U.S. Congress. These policies are simulated using assumptions that allow to reproduce the business as usual scenario published by the Energy Information Administration (EIA) of the U.S. Department of Energy (DoE) (EIA, 2007) and include the Corporate Average Fuel Efficiency (CAFE) provision (H.R. 1506), which has been incorporated into the H.R. 6 bill, and the Renewable Portfolio Standard (RPS) proposal (H.R. 2927), for which an agreement at the Federal level hasn't been reached yet.

These same policies are simulated with the North America model as well, to investigate what their likely impact in mitigating the effect of an early oil production peak may be.

In both studies, emphasis has been put on policies promoting renewable energy, energy conservation and energy efficiency, due to the current inclination in the policy debate to promote interventions that would limit carbon emissions to reduce environmental concerns (Stern, 2007). Te policy debate is also influenced by ever increasing issues related to the production of unconventional liquid fuels (Kaufmann and Shiers, 2008) (e.g. coal to liquids (Vallentin, 2008)).

Structure

The Energy sphere of T21-North America is built upon 13 sectors and 66 modules, while the USA model accounts for 12 sector and 57 modules (see Table 4). Ten building blocks were created to simplify the customization of the models and increase its transparency.

In order to build and customize these versions of the Threshold 21 model, about 750 data series have been examined. All of them have been useful to identify causal relations and correlations and define the structure of the models. In general, these data series can be divided in two categories: exogenous inputs (including single values used to initialize the model in 1980 and historical series used as inputs, i.e. policy variables) and historical data loaded into the model only to compare them to the simulated behavior. About 20% out of the 750 data series is actually needed to correctly initialize and simulate the model.

The Energy Sphere of the T21 North America and USA models account for oil, natural gas, coal, nuclear, and renewable resources (wind, solar, geothermal, hydroelectric and biomass). Electricity is represented as secondary energy form and can be obtained for any of the energy sources above. The energy modules in these models endogenously represent the dynamics of energy demand and production.

The structure of T21 North America and USA include the following main sectors:

- Energy demand: disaggregated into residential, commercial, industrial, and transportation sectors for the U.S., aggregated for China, India, Canada and Mexico. Demand is based on GDP, technology, energy prices, and substitution among energy sources. Demand affects, among others, energy production, trade, prices, and investments.
- Energy supply: oil (US48 and Alaska are analyzed separately), natural gas, coal, nuclear energy, renewable energy, and electricity (by fuel) are calculated for the U.S., Canada, Mexico and the rest of the world. Energy supply is calculated based on demand, availability of resources (for fossil fuels), capital installed, profitability of the market, and exogenous decisions (policies on renewable resource production). Energy supply impacts, among others, consumption, prices, trade, and generation of pollutant emissions.
- Energy prices and costs: oil, gas, coal, renewable, and electricity prices. Fossil fuel prices, calculated for both the U.S. and the global energy market, are based on reserve and resource availability over the medium and long term; electricity price is calculated considering the weighted cost of the energy sources utilized to produce it. Since renewable resources production depends on exogenous decisions, scale of production and technological development, their prices and costs are introduced as exogenous inputs into the model. Energy prices and costs influence demand, investment, and production in the energy sector, as well as production in the economic sectors.

- Energy investment: endogenous (oil, gas, coal), partially exogenous (renewable, nuclear). Investment is based on market profitability (both per each energy source separately and the whole market), technology, and production (which indirectly takes into account the effect of resources availability and demand). Investment directly impacts energy source production capacity and technology improvement.
- Energy Technology: energy consumption (for the four demand sectors), exploration, development and recovery (for fossil fuels, separately), and vehicle technology. Energy technology is calculated based on investment and energy prices. It affects resource availability and production (in the case of fossil fuels, through exploration, development, and discovery), demand, prices (indirectly), and investment (through the average energy technology available).
- Pollution: emissions (CO_2, CH_4, N_2O, SO_X, GHG), carbon cycle, climate change. Pollution is based on fossil fuel consumption; it affects carbon cycle and climate change, as well as life expectancy (social sector). The emission sectors are particularly useful for defining policies aimed at reducing GHG generation and reducing air pollution.

Global energy modules, representing the Rest of the World, include energy demand (oil, gas, and coal with specific modules dedicated to China and India's fossil fuel demand); energy supply (oil, gas, coal); pollution (emissions -CO_2, CH_4, N_2O, SO_X, and GHG). In the case of Canada and Mexico, in the North America model, demand and supply are calculated for all energy sources, allowing for the calculation of trade flows for fossil fuels.

Table 4: The energy sectors of T21-USA and corresponding modules

USA and North America Models - Energy and Environmental Sectors and Modules	
Land	55. Resources Cost
24. Land	56. Resources Cost: Electricity
Sectoral Energy Demand Sector:	**Energy Investments and Capital Sector:**
25. Energy Demand: Residential	57. Energy Prices
26. Energy Demand: Commercial	58. Energy Markup
27. Energy Demand: Industrial	59. Energy Investment
28. Energy Demand: Transportation	60. Energy Investment: Oil
29. Energy Demand: Transportation Fleet	61. Energy Resources Capital
30. Effect of Price on Demand	**Energy Technology Sector:**
Energy Demand and Import Sector:	62. Energy Resources Technology
31. Demand and Import: Oil	**Energy Expenditure:**
32. Demand and Import: Synfuel and Biofuel	63. Energy Expenditure (Nominal)
33. Demand and Import: Natural Gas	64. Energy Expenditure (Real)
34. Demand and Import: Coal	**Emissions and Climate Change Sector:**
35. Demand and Import: Nuclear Energy	65. U.S. Fossil Fuel Emissions
36. Demand and Import: Ren. Resources	66. U.S. GHG Emissions and Footprint
37. Demand and Import: Electricity	67. U.S. Carbon Cycle
38. U.S. Energy Demand by Source	68. U.S. Climate Change
39. U.S. Total Energy Demand	**Rest of the World Production Sector:**
Energy Production Sector:	69. ROW Production: Oil
40. U.S. Total Energy Production	70. ROW Production: Natural Gas
41. Production: Oil	71. ROW Production: Coal
42. Production: Oil Exploration	72. ROW Production: Synfuel and Biofuel
43. Production: Oil Development	**Rest of the World Price and Cost Sector:**
44. Production: Oil Technology	73. ROW Resources Price and Cost: Oil
45. Production: U.S. Oil Production Trend	74. ROW Resources Price
46. Production: Oil Alaska	75. ROW Resources Cost
47. Production: Natural Gas	**China and India Energy Demand Sector:**
48. Production: Coal	76. ROW Energy Demand: China
49. Production: Nuclear Energy	77. ROW Energy Demand: India
50. Production: Renewable Resources	**ROW Emissions Sector:**
51. Production: Electricity Fuel Demand	78. World Fossil Fuel Emissions
52. Production: Electricity Generation by Fuel	79. World GHG Emissions and Footprint
Energy Prices and Costs Sector:	80. Fossil Fuels Balance
53. Resources Price and Cost: Oil	81. Indicators
54. Resources Price	
North America Model – Additional Modules	
US Modules:	**Canada and Mexico Demand and Supply Sector:**
82. EROI	85. Assumptions
83. Production: US Ethanol	86. Energy Demand
84. Cheese Slicer	87. Energy Production
	88. Energy Trade

	89. Electricity Generation
	90. Fossil Fuel and GHG Emissions

The energy sectors of the T21 North America and USA models have been created and customized based on a set of building blocks. These standard modules have been used to represent similar structures and are customized to represent different energy sources, sectors and regions of the world (see table below).

Table 5: Building blocks of the energy sectors of T21-USA and North America

Building blocks	*Where it is used*
Energy Demand	Residential, Commercial, Industrial, Transportation
Demand and Import	Oil, Coal, Natural Gas
Energy Resources Production	Oil Alaska, Coal, Natural Gas
Energy Resources Price	Oil, Coal, Natural Gas
Energy Resources Cost	Oil, Coal, Natural Gas
Energy Resources Capital	Coal, Natural Gas, Renewable Resources
Energy Resources Technology	Coal, Natural Gas, Renewable Resources
Fossil Fuel Emissions	US, Canada, Mexico and ROW
GHG Emissions and Footprint	US and ROW
ROW energy Demand	China, India, Canada and Mexico

The energy demand building block is used to represent residential, commercial, industrial, and transportation energy needs. The causal structure and mechanisms governing energy demand for these sectors are very similar. All of them depend on energy prices, GDP and technology. All the parameters of the module are different per each sector and changes have been introduced where needed (e.g. coal is not considered a source of energy for transportation, therefore it is not included in the corresponding module), both in the structure of the modules and in the formulation of specific equations.

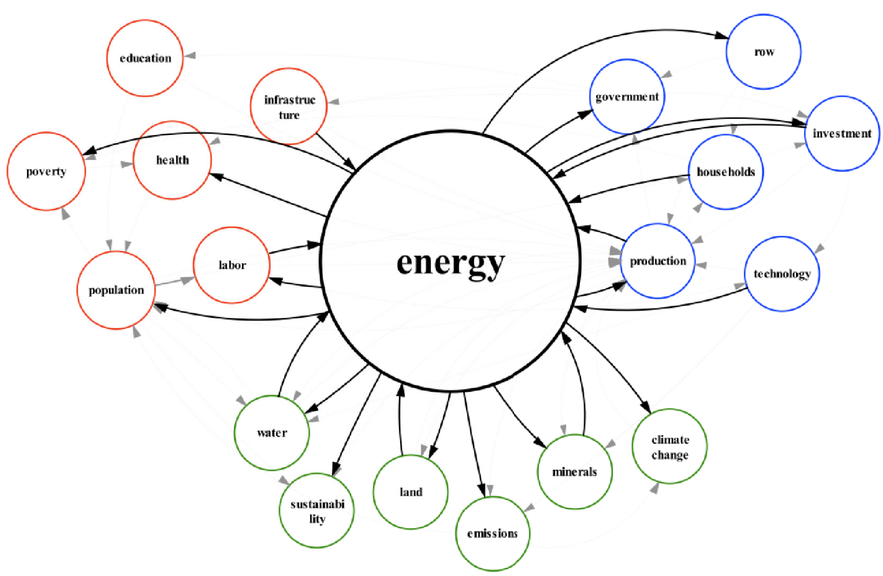
The production block, as well as demand and import, price, cost, capital and technology, are used to represent dynamics related to different non-renewable energy sources. Again, the causal mechanisms defining production, demand and import, price and cost, are very similar for the fossil fuels considered in the model. Similarly, capital and technology follow the same path for every energy source.

The three remaining building blocks involve the rest of world (ROW). Fossil fuels and GHG emissions modules are built for both U.S., Canada, Mexico and ROW (aggregated), while the energy demand block is built for China, India, Canada and Mexico (U.S. and ROW energy demand are represented in more detail with different causal structures).

Feedbacks

The main feedback loops existing among energy and the other modules, sectors, and spheres of the model can be summarized in Figure 3 below. This diagram shows the main relationships existing between the environmental, economic, and social spheres in T21-USA. Emphasis has been put on the energy sectors in order to investigate in more details their impacts on the rest of the model.

Figure 4: Conceptual overview of T21-USA and North America



Energy prices influence economic production. A higher energy price can be seen as a higher cost for businesses and households (in fact, when energy prices increase, the purchasing power of households is reduced -all else equal-). When energy prices rise, expenses increase (even if the same amount of goods is traded) while revenues remain constant. These effects generate a decrease in production growth, which provokes a reduction in energy demand and a subsequent drop of energy prices (at least in the short term, before depletion becomes the strongest factor driving the behavior of energy prices).

Energy prices also influence energy demand and technological development of exploration and recovery activities. The explanation is straightforward: the higher the energy price, the lower the energy demand; similarly, the higher the energy prices, the higher the development of technologies associated with consumption, exploration, and recovery. Both a reduction of the demand and the development of more effective (for exploration and recovery) and efficient (for consumption) technology generate a reduction of the energy price (at least in the short term). Energy investment mainly depends on GDP and energy demand: when the latter increases, investments, which are part of GDP, are put in place to guarantee higher energy availability for the future. Energy investment therefore increases potential energy production that is transformed into actual production if energy resources are available. If they are, production takes place and reserves are depleted, generating a price increase (all else equal). As explained above, high energy prices reduce the growth rate of GDP, a factor that reduces investments and demand across the board (including a negative impact on energy investments, partly offsetting the incentive to increase such investments due to the increase in energy prices).

Energy demand depends on energy prices, GDP, technology, and population (for what concerns gasoline demand). Demand for energy is influenced by GDP in two ways: the higher the income, the higher the demand and consumption, and at the same time the higher the demand, the higher the investment in technology (which increases consumption efficiency) given the limited availability of resources.

Energy demand influences energy prices, investment, production, and the creation of fossil fuels emissions (which is defined by consumption: the minimum between demand and production). Energy investment and production generate feedbacks acting through prices, mechanisms that have been explained above, while emissions create a relationship with the social sphere of the model. Given that the higher the demand for energy, the higher is the generation of fossil fuels emissions (assuming that production follows demand), emissions have two effects on society: an alteration of the air quality that provokes a reduction of both quality of life (health) and life expectancy (population) in the long term. The latter reduces energy demand.

Energy technology is influenced by prices and availability of resources, and it affects energy demand and supply. Technology associated with consumption and production needs to be improved when energy prices increase or stabilize over a sustainable threshold and when new energy sources need to be introduced in the market due to depletion of conventional ones (renewables for fossil fuels). Different kinds of technology require consideration (e.g. consumption, exploration, development, and recovery) due to the nature of their impact on environment, society, and economy. Three balancing loops characterize the development of energy technology: the faster its improvement, the smaller the demand for energy (consumption technology) and the more efficient the production of energy (exploration and recovery technology). Both effects reduce energy prices and therefore the need for improved technology. On the other hand, when production becomes more efficient, depletion is still in place, indicating the need for further technology development.

Energy production is influenced by investments (capital installed), technology (exploration and recovery), demand, and availability of resources. These factors can be organized in potential production (capital and resource availability, which is equal to recoverable reserve, obtained by the combination of technology and resource in place) and demand. Energy production affects resource availability (depletion), generation of fossil fuels emissions, and revenues of the government. Gasoline and fossil fuels consumption are taxed by the government, and represent an important source of revenue that contributes to national economic growth, as well as to energy demand and production.

Energy resources are influenced by energy production: the higher the production, the faster the depletion process of fossil fuels reserves. The availability of resources and reserves affects energy prices technology and production. Emissions are influenced by energy consumption (the minimum between demand and production). As mentioned above, fossil fuels emissions affect population (life expectancy) and health (air quality). In addition, emissions generate GHG, which, according to a growing number of studies (IPCC, 2007), strengthen the actual process of climate change.

Two additional considerations can be made, even though the model does not explicitly represent them:

- Petrodollars[6] are an important foreign source of financing for the government, if oil is substituted by domestic renewable energy sources, the present equilibrium in the flow of foreign investments might change. The balance of payments may decline but the USA loses an important source of financing without being prepared to face its consequences.
- Extraction, production, and transportation of fossil fuels can damage and modify irreversibly the environment.

4.3.4 Transportation Energy Module

There has been a long-standing perception between both the general public and policy makers that the goals of economic growth, environmental protection, and

[6] A petrodollar is a dollar earned by a country through the sale of petroleum. In the OPEC countries, it is mainly the sale of crude oil that allows nations to prosper economically and invest in the economies of those countries that purchased their oil. The term was coined by Ibrahim Owiess in 1973.

reduced oil use involve a complex set of trade-offs, with national defense goals tightly coupled with creating direct oil substitutes for liquid fuels. This case study aims at analyzing the impacts of the creation of a parallel non-oil transportation system based on the expansion of existing electrified rail systems, both urban and freight. Employing an integrated energy model such as T21-USA allows to identify bottlenecks (such as an increase in emissions due to the utilization of coal to supply growing electricity needs), as well as synergies (such as using renewable energy to supply the incremental energy needs). In addition, economic and environmental impacts can be estimated and evaluated, including the impact of the needed investment on GDP and on households' accounts, as well as the avoided cost for oil consumption and decreasing dependence on foreign energy sources.

The transportation energy model was developed and integrated into T21-USA to enhance the structural formulation previously used in the transportation sector. Such addition allows for the representation of the dynamics of energy demand in the transportation sectors, which account for electricity (i.e. passenger vehicles and rail), gasoline and jet fuel, biofuels and natural gas. Urban and freight rail are separately represented using exogenous goals that are translated into effective miles converted per year and their correspondent electricity demand. Such demand, which grows according to the advancement in converting rail miles, reduces oil consumption.

Expanding electrified rail also generates employment while reducing oil consumption. The increasing needs for electricity can be satisfied by investment in power generation capacity from renewable energy, further contributing to curtailing oil demand and emissions. National defense goals would be met by such a paradigm shift, in fact military uses of energy would benefit from less competition for oil from critical needs especially under oil-constrained scenarios.

4.3.5 Industry Energy Modules

Most of the debate around climate policy in the U.S. Congress has until recently revolved around promoting cleaner forms of energy generation (i.e. RPS) and automotive transportation (i.e. CAFE). In 2008, the main focus of the debate has begun to shift to consideration of legislation that would establish a comprehensive, economy-wide cap-and-trade system that places a price on carbon- and other greenhouse gas-emissions.

The industry energy model (Integrated Industry-Climate Policy Model, II-CPM) was built to compare the National Commission on Energy Policy (NCEP) cap-and-trade proposal embodied in the legislation offered by U.S. Senators Jeff Bingaman (D-NM) and Arlen Specter (R-PA), the Low Carbon Economy Act of 2007 (S. 1766), with variations of the Lieberman-Warner Climate Security Act of 2007 (S. 2191). The implications of other measures (e.g., allowance allocations, trade provisions, R&D investments) associated with these proposals also have been explored.

Employing a computer-based, System Dynamics modeling approach, supplemented by econometric and qualitative analyses, the study investigates three questions:

Cost Impacts

- How will climate policy-driven energy price increases affect the production costs and profitability of manufacturers in energy-intensive manufacturing sectors?

International Market Impacts

- In the face of energy-driven cost increases, and constraints on manufacturers' ability to pass these costs along to consumers, how will international competition affect the industry's competitiveness (i.e., profitability and market share)?

Investment Options and Opportunities

- How will manufacturers respond to the energy price increases and possible threats to their competitiveness? For example, would firms adopt new energy saving practices and technologies, expand or reduce production capacity, or move operations or plants offshore?

The structure of the simulation models created to carry out the analysis of climate change impacts on the competitiveness of energy-intensive manufacturing sectors include modules customized to the aluminum (primary and secondary), steel, paper and chemicals (petrochemicals and alkalies and chlorine) sectors. A generalized model has been first developed and then customized to represent (1) the cost structure of the six industries analyzed, (2) the impact of international markets and (3) investment options in energy efficiency capital and technology.

The cost structure module, which adopts the Annual Survey of Manufacturers classification (NAICS), calculates total production costs as the sum of energy, labor, capital and material costs. Energy costs are calculated for electricity, direct and feedstock fuel consumption. The energy sources considered include electricity, coal, coal coke, distillate fuel oil, residual fuel oil, LPG and natural gas. In addition, operating surplus and operating margin are calculated for all industries, using both total revenues and production costs. Domestic production, both for domestic consumption and export, is defined using GDP (exogenous input obtained from NEMS (EIA, 2003) or T21-USA) and domestic market share, which is calculated in the Market module.

The market module calculates domestic market share, its most important endogenous variable, using the ratio between domestic and international prices. International import prices are exogenously calculated using import quantities and customs values, plus import charges, for the main exporters to the U.S. (e.g. Canada, Russia, Venezuela, Brazil, EU15, China and rest of the world, for the aluminum sector). Market share is used to define domestic production (both for domestic consumption and export) out of total demand (for domestic consumption and export).

The investment module is used to estimate the potential impact of investment in energy efficiency on total production cost and profitability. Fuel intensity (demand per unit of production) is exogenously calculated with MECS data and projected using various assumptions including: (1) baseline technological development (i.e. 0.25% a year), (2) 5% annual increase in energy efficiency and (3) energy efficiency improvement that compensates the increase in energy cost correspondent to the three pricing scenarios considered (i.e. S.1766, S.2191 and S.2191 with no offsets).

The II-CP model examines the impacts of energy price changes resulting from different carbon-pricing policies on the competitiveness of selected energy-intensive industries, especially in the face of international competition. It further examines possible industry responses, and identifies and provides a preliminary evaluation of potential opportunities to mitigate these impacts. The main feedbacks included in the model therefore identify the effect of increasing energy prices and material cost on market share, through the simulation of cost pass-along scenarios, and on improvements in energy efficiency needed to offset growing energy expenditure.

The feedback on market responses accounts for all domestic production cost changes and their impact on domestic market share. These include changes in labor, material and energy costs, which include electricity, direct and feedstock fuel use. Energy consumption is defined using aluminum demand, in the aluminum sector, and prices impacts, accounted for in the market share calculation.

Similarly, energy efficiency is calculated using a reference exogenous input, which represents business as usual longer-term technology improvements, and the impact of increasing energy prices. Increasing energy efficiency has an impact in turns on energy consumption and expenditure.

4.4 Research Analysis

Whether as part of the Kyoto Protocol, the European Union Emission Trading Scheme, or a different regulatory framework, policy measures to solve the upcoming energy issues and mitigate the impacts of climate change will focus on limiting CO_2 and other greenhouse gas (GHG) emissions. In practice, policy makers can support the shift to clean and renewable energy in various ways. Generally, they can use a “command and control” approach or formulate “incentive-based” policies (CBO, 2008). With respect to fossil fuel emissions, the former would consist in introducing mandates on how much individual entities could emit or what technologies they should use; the latter would imply a tax on emissions or a cap on the total annual level of emissions combined with a system of tradable emission allowances. The modification of existing legislation is of course as relevant as the introduction of new policies. The removal of subsidies for the production of fossil fuels, which has been largely discussed by the government in 2007 and 2008 (Hasset and Metcalf, 2008), is a good example. Different instruments can be used to support the diversification of supply and containment of demand. These include subsidies, incentives (e.g. feed-in tariffs), taxation and efficiency mandates. Governments can therefore support the development (1) and adoption (2) of energy efficient technology, (3) facilitate the shift to cleaner energy sources. The general public and the industry can instead (4) reduce consumption by conserving energy, (5) adopt new and more energy efficient technology/appliances and (6) recycle waste that can be used for energy generation (e.g. electricity and biofuels) and production of commodities.

The present research work intends to investigate whether the global, regional and national context becomes relevant when formulating and implementing new policies. Their effectiveness, with respect to the intended medium and longer-term goals, is analyzed. In order to carry out such study, a number of scenarios and policy options are simulated. Policies account for both subsidies and taxation of energy prices, the implementation of increased efficiency standards and modified trade agreements. Particular emphasis has been put on the impact of such intervention on energy consumption (e.g. through the simulation of policies that would increase energy efficiency of passenger vehicles, rail, energy intensive industries and power sector), and the resulting energy supply mix. Scenarios used to evaluate the impacts of the selected policies include:

- Medium and low availability of oil reserves, as indicated by the US Geological Survey (USGS 2000);
- Disruption of oil reserves due to exogenous events (e.g. attack to reservoirs and riots) and to overproduction of oil fields (Simmons, 2005);
- Elasticity of GDP to energy prices;
- Technological development (i.e. on top of endogenously calculated improvements) for fossil fuel exploration, development and recovery processes;
- Technological development (i.e. on top of endogenously calculated improvements) for energy conservation, for the residential commercial and industrial sectors.
- Miles driven per vehicle per year (i.e. how many miles per vehicle in the U.S are driven on average in a year) (CBO, 2008);
- Energy Return on Energy Investment (EROI) for corn ethanol (Hall et Al., 2007);
- Biofuels price;
- Market prices, domestic and global, for aluminum, steel, paper and chemicals (energy intensive industries case study only).

The present study covers a variety of policy proposals using a consistent integrated framework customized to Ecuador, North America and USA. The latter was further expanded to represent urban and freight rail as well as energy intensive industries in the U.S. The models aim at representing the context in which policies are formulated and approved by extending the analysis to their social, economic and environmental impacts. More specifically, the following policies are simulated and analyzed:

1. The use of subsidies: analyzed in relation to support for the ethanol industry, formerly promoted by G. W. Bush and supported by the U.S. Senate, Republican Party and lobbies. In the case of Ecuador, the impact of subsidizing electricity price on household and government accounts as well as on energy consumption is analyzed.
2. Cap-and-trade legislations: investigated through the proposals of Bingaman-Specter (S.1766) and Lieberman-Warner (S. 2191), accounting for the modifications suggested by the National Commission on Energy Policy (NCEP), which include allowance allocation, cost containment and international offsets.
3. Taxation: analyzed for the introduction of a carbon tax and for older proposals, including the one of Rep. Roscoe Bartlett, to increase gasoline taxes and reduce income taxes in order to offset the increase in government revenues and redistribute wealth to the lowest income classes.
4. The introduction of new mandates on energy efficiency: analyzed through the simulation of the proposed new CAFE (H.R. 1506 and H.R. 2927). A push toward electrified freight and urban rail for the U.S. to reach European efficiency standards and network density is also tested. The impacts of the adoption of energy efficient technology and appliances is tested for Ecuador, based on household surveys carried out by SolarQuest in the Galapagos, and

for energy intensive industries (aluminum, steel, paper and chemicals) as part of NCEP proposal.

5. The introduction of new mandates on renewable energy production: analyzed through the simulation of Federal Renewable Portfolio Standards (RPS, H.R. 969 and ACORE 2007 outlook).
6. Energy conservation in the residential, but also commercial and industrial sectors is tested for the U.S. A McKinsey report or climate change is used as a starting point for the analysis (McKinsey, 2007).

One of the values of this study consist in proposing an integrated analysis of the impacts resulting from the implementation of individual policies, as well as of combination of policies, over the medium and longer term, under a variety of scenarios and for a variety of indicators in the social, economic and environmental sphere.

The analysis of the case studies proposed has profited from the input and support of various organizations and research institutes, in primis the Millennium Institute. Additional support was received by: Allan Baer, SolarQuest – *Republic of Ecuador study*; Dick Lawrence and Charlie Hall, ASPO-USA and SUNY-ESF – *North America study*; Jay Harris, the Changing Horizon Fund – *USA study;* Hon. Rep. Roscoe Bartlett, US Congress, and his staff – *CAFE and RPS bills*; Alan Drake and Ed Tennyson – *transportation study*; Joel Yudken and Tracy Terry, High Road Strategies and National Commission on Energy Policy (NCEP) – *energy intensive industries study*.

5. Main Findings

5.1 Introduction

Contextualizing energy issues facilitates their understanding and supports the processes of decision-making. An explicit representation of the context in which energy policies are formulated allows for a rational representation of both the dynamic and detailed complexity that characterizes them. The representation of dynamic complexity is obtained through the inclusion of feedback loops, delays, and non-linearity in the T21 framework utilized. This allows for the identification of various unintended consequences and synergies when investigating forward-looking scenarios, which would not be found when utilizing optimization and econometric tools.

From a global point of view, the analysis of the conclusions of the Stern Report suggests that contextualizing energy issues is relevant when formulating longer term policies by showing that global studies may not correctly represent national contexts appropriately (Stern, 2007). The case of the Republic of Ecuador shows that while politically oriented measures can support the stability of the country, more integrated energy policies can reduce emissions while increasing revenues for the government, improving social services and lowering households' expenditure.

In the case of North America, unintended consequences emerged when simulating various energy policies in isolation. Such policies were also unable to mitigate the impacts of prolonged oil shortages in the short term, a scenario with no precedents in history but realistic.

The analysis of U.S. energy policies shows that the framework used is consistent with conventional energy models when similar assumptions are simulated, highlighting its flexibility and transparency. In addition, results of the simulation unveil side effects and policy resistance in the case of CAFE and RPS, while showing that relations existing among energy and society, economy and environment justify investments in renewable energy at current prices. The significance of accounting for both global, national and sectoral dimensions is examined in the study of the impacts of climate change policy proposals (i.e. cap-and-trade) on U.S. energy intensive manufacturing industries.

5.2 Global Perspective: Ecuador

Utilizing a key conclusion of the Stern Review on the Economics of Climate Change – that is, an annual investment of 1% of world Gross Domestic Product (GDP) to mitigate the negative economic impacts of climate change (Stern, 2007)– the author summarizes the application of T21 to a country-wide analysis for the Republic of Ecuador (Ecuador). The analysis of Ecuador assumed an investment of 1% of GDP in energy efficiency and renewable energy technologies to measure the potential to stabilize carbon emissions from fossil fuel electric power generation.

When looking at the baseline scenario, Ecuador seems to be headed toward increases in greenhouse gas emissions, which will reach 35.6 million tons/yr by 2025, a 50% growth from 2007 (23.63 million tons/yr) levels. The immediate cause of this rise is growing fossil fuel consumption that reaches 472 trillion Btu from a 2007 value of 309.2 trillion Btu. Ecuador's population growth from 10 million in 1990 to 17 million in 2025, is party responsible for this rise in energy demand. Energy consumption, however, is raising at a much faster rate, driven more by the increase in real GDP, which doubles near 2015. Retail sales of electricity in the residential sector begin at 4 million Kwh in 2007 and grow to 7 million Kwh by 2025. Electricity sales are growing at a faster rate than overall energy demand, reflective of a disproportional increase in the demand for residential electricity as population and GDP grow. In order to meet this rising electric power demand, fossil fuel installed capacity increases to 5500 MW.

Hydroelectric generation shows minimal potential expansion in Ecuador, meaning that increased demand for electricity must be met by augmenting fossil fuel capacity. Correspondingly, the fraction of electricity generated by hydro is projected to decrease to 27% in 2030 from 50% in 2007. In 2006, total government expenditures (in nominal USD) totaled $8.57 billion, $30.67 million of which are spent in the energy sector. Total government investments in 2006 are $1.93 billion, compared with $5 billion of private investments. Per capita real disposable income in Ecuador remained nearly constant from 1990-2007 as the country recovered from the 1999 financial crisis. After 2007 per capita income is projected to rise, assuming the Ecuadorian currency remains strong. Ecuador's expenditures in health, education and roads rise with increasing government spending, producing 100% average adult literacy rates by 2021, and 95% in 2010. Access to basic health care also reaches about 100% by 2010. Maintaining business as usual assumptions, Ecuador shows gradual improvements in quality of life, unfortunately accompanied by the growth in fossil fuel consumption and carbon emissions.

Four scenarios were simulated to analyze the current energy policy debate in Ecuador and options for reducing emissions. The first one simulates Ecuador's newly elected president Correa’s proposition to advocate government subsidies to reduce the price of electricity. Lowering the cost for consumers is a political move designed to increase his draw with voters. This policy, although it is projected to increase the disposable income of the population (more for the rich than for the lower income classes), may conversely increase electricity demand and worsen greenhouse gas emissions. This measure may also cause a short-term rise in GDP, as total factor productivity increases due to higher access to electricity. The second scenario includes the recommendation to invest 1% of Ecuador's GDP in energy efficiency within the power sector only. The adoption of efficient capital has the potential to reduce electricity demand even as population and per capita consumption increase, as well as produce customer savings through avoided costs, 33% of which are assumed to be reinvested. Reduced demand for electricity also decreases the need for the expansion of fossil fuel capacity and consumption, thereby producing a net decrease in emissions.

In the third scenario, the author maintained the contribution of renewable energy at 2007 levels, or 50%. Therefore, in order to meet increasing power demand, renewable energy installed capacity will have to increase alongside fossil fuel capacity.

In the fourth and last scenario, the author projected that electricity imports would increase from 7 to 15% by 2025, provided that oil prices increase or remain stable, generating increasing revenues for the government (from exports rather than from thermal electricity production).

While each of these scenarios provides its own benefits and disadvantages, the most effective policy recommendation must take into account the realities of each of the spheres that comprise society. Thus, the political reality that President Correa will seek popularity with voters must be taken into consideration together with the environmental goal of reduced emissions. Our recommended policy seeks to take all of these factors into consideration and provide the present, near future, and long-term benefits associated with each of the described scenarios. As a consequence, for the short term, President Correa should increase subsidies for electricity. As discussed, this will decrease energy prices and increase disposable income for the citizens of Ecuador. In order to address lowering emissions, the author suggests both the implementation RPS and the allocation of investment in energy efficiency. These accounts for increasing consumer energy efficiency through investment in technology, and decreasing production of electricity with fossil fuels by investing in renewable energy sources. The resulting lowered demand for electricity then translates into a near-future decrease in fossil fuel consumption and carbon emissions. In order to effectively reduce emissions in the long term, the role of fossil fuel in the energy mix must be drastically reduced. The analysis of Ecuador shows that capping the use of fossil fuels for electricity production (e.g. RPS set at 50%) at its current level, is as a very effective policy. The other half of electricity production would come from increased investment in renewable energy. Since increasing renewable energy installed capacity requires years of infrastructure construction, this policy is intended to take effect in 5 to 10 years. Possible sources of funding for this measure were not addressed in our analysis.

The Ecuador case study indicates that the combination of the comprehensive policy recommendation mentioned above would stabilize carbon emissions generated by the electric sector around 2010 levels. It is worth noting that these measures, while they would reduce emissions, only stabilize them for the electricity sector and do not lead to an overall decrease in national emissions. To reach 1990 emissions levels would require a much greater investment of funds. This conclusion originates from the observation that investing in energy efficiency in non-electric sectors is not trivial. In fact, when looking at transportation or industry, capital is characterized by a long lifetime and its replacement value is higher than in the electric sector. Furthermore, investing in the electricity sector does not put a heavy load on the citizens, while impacting non-electric sectors requires a strong and active participation (investment) of the population, which is currently facing poverty. On the other hand, the overall results in reducing emissions may be more encouraging when investing also in non-electric sectors, but delay times would be higher and the economy may suffer significantly, with the risk to slow down the growth of disposable income observed in the baseline scenario (this analysis is carried out for North America and the USA). Thus, our analyses indicate that a much greater investment than the Stern Report's suggested 1% of GDP will be necessary to achieve quick significant reductions in greenhouse gas emissions in Ecuador.

5.3 Regional Perspective: North America

In the case study of the Republic of Ecuador the author assumed a continuation of current trends, excluding the analysis of events that may significantly impact the energy sector, such as natural disasters and global warming. (e.g. sea level rise and glacier melting in the Andean Region).

Also, the scenarios simulated with the Ecuador model did not include intervention in non-power energy sectors, such as transportation. The North America and USA models expand the integrated analysis carried out for Ecuador to include the new scenarios and policies mentioned above.

The policy choices of T21-NA range across energy, society, economy, and the environment. The model also simulates various scenarios on world conventional oil availability, including an unexpected peak in production as early as 2011 as well as EIA's forecast (Wood et al., 2003) (e.g. USGS Low 2.2 trillion barrels-, and USGS Medium Estimate -3 Trillion barrels (USGS 2000)), with the latter being also accepted by Hirsch (Hirsch, 2005)).

Taxes on gasoline or income, as well as the introduction of commercially viable breakthrough technology can be tested with the model while simulating the impact of improved Corporate Average Fuel Economy (CAFE) standards or the approval of a Federal Renewable Portfolio Standard (RPS). The North America study analyzes three main groups of policy options in the context of both low and medium oil availability (i.e. URR): Market Based, Maximum Push for Renewables, and Low Carbon Emissions. The former serves as the Reference Scenario proposed by ASPO-USA. It is based on a market economy, where (1) Federal laws do not regulate electricity production from renewable energy sources, (2) there is no restriction on CO_2 emissions, and (3) heavy subsidies for ethanol are allocated as proposed by the U.S. Department of Agriculture (USDA) until 2016 (USDA 2007). The Maximum Push for Renewables scenario simulates what would happen if there were large Federal support for bringing renewable energy

on line in the near future. It is therefore assumed that, in this scenario, a Renewable Portfolio Standard (RPS) of 20% by 2020 is approved by the U.S. Congress, as proposed by H.R. 969, that there are still no restrictions on CO_2 emissions, and that subsidies for ethanol production are retained. The Low Carbon Emissions scenarios add two interventions on top of the implementation of the 20% RPS: the CAFE Standards will be increased (H.R. 1506 by Rep. Markey, new standards for passenger vehicles <10,000 lbs. will be set at 35 mpg by 2018, followed by a 4% increase each year thereafter) and electrification of light urban, commuter, and freight rail introduced.
Both the analysis carried out with the North America and U.S. models focus on policies promoting renewable energy and energy conservation. This is mainly due to the current policy debate, especially to the willingness of the Government to promote interventions that would limit carbon emissions to reduce environmental concerns (Stern, 2007; Farrell et al., 2006)), and to low efficiency and increasing issues related to the production of unconventional liquid fuels (Kaufmann and Shiers, 2008) (e.g. coal to liquids (Vallentin, 2008)). These direct substitutes for oil are accounted for, and explicitly represented (e.g. Canadian tar sands) in the models used, but they are not analyzed in detail concerning policy propositions aimed at subsidizing production or increasing output.

The simulations of T21 North America show that there is no silver bullet that will solve our energy needs. An example is the fact that increasing production of first generation corn ethanol, as projected by USDA, would offer a net contribution to the transportation sector smaller than 4%, in spite of very high water requirements and considerable subsidies. Nevertheless, a solution lies in developing a strong renewable energy system that minimizes GHG emissions along with a program to reduce demand. In addition, projected fossil fuel production will significantly change in the future relative to 2007, adding to the uncertainty related to international trade and national policy planning. Elaborating a coherent energy plan therefore requires the integration of various interconnected interventions, some of which are analyzed below.

Results of the analysis indicate that when oil production turns downwards in 2011 at 29.5 Mb/year (Low URR scenarios), real oil prices would jump to $285 per barrel (in year 2000 dollars) while GDP declines by 9% in all Low URR scenarios. High prices and falling GDP drive a reduction in energy demand (-5%), which makes oil prices decline to $190 in 2013. Furthermore, declining oil prices, as observed in 1983 and 1984, allow a less energy intensive economy to recover faster from the oil shock (due to energy conservation). In fact, the GDP growth rate turns positive in 2014 and oscillates around zero until the energy transition is fully completed by 2025. Interestingly, when simulating the Medium URR scenarios, the longer term economic performance of the region will be poorer, due to a slow adjustment of consumer demand that does not allow for a fast and effective transition (e.g. adaptive expectations) beyond oil. Over the longer term, though demand for oil is rapidly decreasing, forced by declining supply, oil prices will keep increasing due to the higher cost of extraction from less accessible reservoirs -that will become a larger portion of the supply base-, reaching $300 in 2050. Consistently, the energy return on investment for oil and gas is projected to decline, reaching a ratio lower than 8:1 in 2050 for economically recoverable wells (results of the simulation show a value of 25:1 in 1980). These values should raise concerns about future economic growth according to Gagnon (Gagnon, 2008).

A push towards renewables and substitution for oil (Renewable and Emissions scenarios), allows the economy to reduce its dependence on expensive energy only in the medium to longer term, due to delays in capacity building. As a consequence, average energy price declines and is constantly lower than in the Market Based scenario (by about 18%), after 2020 and throughout the simulation. It has to be noted that, when simulating the Renewable and Emissions scenarios, electricity generation from renewable energy sources grows considerably.

Therefore, the average cost of electricity increases (+40% with respect to the Market Based scenario), especially when both renewable push and electrification of rail are assumed to take place. Nevertheless, the high price to pay for electricity is generally offset by the savings generated by a reduced consumption of oil and more expensive fossil fuels, and both households and GDP profit from it. Worth to be noted, when simulating RPS in isolation, coal use for electricity generation increases driven by higher GDP after 2020. RPS bills propose to increase electricity generated with renewable energy to 20% by 2020, a considerable achievement from about 8% in 2007, which includes hydro. After 2020 these bills propose to keep the 20% share constant, allowing for a much smaller push to increase renewable energy generation. In this case, electricity generation from renewables will grow only by about 2% a year given its strong interdependency with GDP, and the use of coal will increase again.

In all scenarios with limited oil supply, support to the government is needed to contain debt. For the U.S. it is assumed that taxation increases (30% of GDP is to be taxed in 2050 in the Low URR scenario and about 26% in the Medium URR case) to allow the Federal Government to avoid the negative spiral of debt and interest rates and keep foreign capital at about 30% of total national investment. When simulating the USGS Medium URR estimation, GDP will grow at a lower rate than Congressional Budget Office (CBO) and Energy Information Administration (EIA) projections in the Market Based and Renewable scenarios, but still faster than in the Low URR case. This is due mainly to the fact that with larger simulated reserves, peak oil and the energy transition are pushed back to 2020, and by then the economy will be less energy intensive and less sensitive to energy prices than in 2011. As previously stated, GDP grows faster in the Renewable and Emissions scenarios than in the Market Based case, but their contribution is smaller than in the Low URR case, where the economy is more sensitive to energy prices and energy efficiency.

The impact of the upcoming energy transition can have relevant impacts on both households and the industry. More in details, households will be affected by growing energy expenditure, which will reduce discretionary consumption in spite of improved energy efficiency and increasing energy conservation. The industry will have to allocate increasing investments in order to produce decreasing amounts of oil and gas from almost fully depleted reservoirs and discretionary investments will be reduced to zero by 2050. Consistently with the results of the model, as energy becomes more expensive, due to (1) the mismatch between demand and supply for oil or (2) the increasing production of electricity from renewable sources, non-discretionary consumption increases (from 39% to 50% of GDP in 2050, Low URR case) while discretionary consumption and investment shrink (from 36% to 15% and from 3% to zero in 2050, Low URR case). As for the latter, when GDP grows slightly (Low URR Market Based scenario), maintenance remains about constant, energy acquisition is pushed upwards from 10% to 22% by the net effect of decreasing energy return on investment –positive- and declining energy demand –negative. Energy input is higher in the Medium URR case due to depletion and a slower energy transition.

Despite declining production and consumption of oil, worldwide CO_2 emissions are projected to increase throughout the simulation, with the only the exception of a few years following peak oil, confirming concerns of environmental consequences even under a peak oil scenario (Brecha, 2008). U.S. emissions decline in all Low URR scenarios by 2050 (reaching about 3.5 Billion Tons per year, -40% with respect to 2006 and well below 1990 levels) and increase in the Medium URR cases (to 8 Billion Tons per year, +33% with respect to current level), driven by increasing GDP and energy demand.

5.4 National Perspective: USA

There has been growing concern in the U.S. Congress about the recent emergence of the critical challenges of energy availability and the impacts of climate change. Both are inextricably linked and dealing with them is fundamental to the progress of America and the rest of the world. In this respect, the USA model is not designed to promote a particular approach. Rather it is structured to test results of different policies and assumptions in a neutral framework, so that it can support effective dialogue among interested parties, encourage coherent actions, and help monitor results.

The T21-USA model results indicate that a continuation of current policies and trends will lead the U.S. to become increasingly dependent on foreign energy resources and more vulnerable to price fluctuations. Furthermore, alternative scenarios simulating improved CAFE and Renewable Portfolio Standards (RPS) show that major reductions in the U.S.' resource consumption and carbon emissions could be possible while stimulating the economy over the medium and longer term. Nevertheless, the model shows that unintended consequences, such as the Jevons Paradox, have to be taken into consideration when defining national energy policies.

The business as usual scenario (reference scenario) relies on the assumption that current (2007) trends will continue and highlights the main challenges the U.S. and the rest of the world will face in the years to come: population and economic growth, trust funds sustainability, energy transition, and climate change. EIA (Wood et al., 2003) and USGS (USGS 2000) assumptions on oil availability are utilized to generate scenarios consistent with NEMS' (EIA, 2003) and CBO's projections (CBO, 2006). Other assumptions simulated with T21-USA include: consumer behavior (e.g. residential energy conservation, yearly vehicle mileage), technology improvement (e.g. energy efficiency enhancement, biofuels production, oil resources -oil recovery technology, overproduction of oil fields).

Policies include: non fossil fuel energy generation (e.g. nuclear and renewable energy generation), CAFE standards, gasoline, carbon, and income taxes.

Among the many different results that can be derived with the T21 model, a few key ones are hereby described:

• The simulation of the new bill on CAFE that proposes to increase the fuel efficiency of new vehicles to 35 mpg by 2020 shows the following results:

- Gasoline consumption decreases to 153 billion gallons in 2050, a reduction of 35% with respect to the business as usual scenario and equal to gasoline consumption in 2006;
- Total oil demand in 2050 is slightly higher than in the business as usual scenario (6.7%) due to the lower demand for oil between 2010 and 2040 that frees up income that generates higher economic growth than in the business as usual scenario, with a slightly lower overall energy price due to the lower demand. GDP, in 2050, is 17% higher in the CAFE scenario with respect to the business as usual simulation;
- Better economic performance drives growing demand for energy, which is higher in 2050 and generates 12% more CO_2 emissions than in the business as usual scenario, despite lower emissions from transport.

• ACORE's Outlook on Renewable Energy in America (ACORE, 2007) states that 635 GW of renewable power capacity can be added by 2025. The results of the simulation of such a scenario can be summarized as follows:

- The share of electricity generation from renewable resources in 2025 is equal to 33%, up from 9.7% in 2006;
- The share of renewable energy demand with respect to total energy demand increases to 21.8% in 2025, from 6.5% in 2006;

- Starting from 2008, GHG and CO_2 emissions are increasingly reduced by about 0.5 billion tons per year until 2025, and are lower than in the business as usual scenario until 2040;
- By 2025 the model projects about 1.5 million employed more than in the business as usual scenario.

• Voluntary actions, such as energy conservation in the residential sector, can contribute to reduce CO_2 and GHG emissions. The simulation of a progressive increase in residential energy conservation to reach 40% by 2050 generates the following results:

– Residential energy demand decreases by 21.5% in 2050;
– GDP is higher than in the business as usual scenario and its growth accelerates towards 2040, after the energy transition takes place;
– GHG emissions are reduced by a small factor.

• The simulation of a best-case scenario that combines improved CAFE for the transportation sector (from cars to trucks), renewable energy investment and cost abatement for biofuels, and energy conservation (for all sectors and especially in transportation) shows that:

– Renewable energy power stabilizes above 24% of total energy demand, while it represents 38% of domestic production and over 25% of electricity production (having reached its maximum penetration rate of 38% in 2025);
– CO_2 emissions stabilize after 2010 at about 6.5 Billion tons/year, while GHG emissions per capita decrease to 17.5 tons/person/year. GHG emissions from 2025 are constantly 2 billion tons lower than in the business as usual scenario;
– The oil price, as well as the average energy price, is lower than in the other scenarios, due to the stable energy demand. The energy transition is smooth

and the gap between fuel demand and supply closes faster than in the BAU scenario. Biofuels in 2050 accounts for 65% of fuel consumption;

- GDP is 40% higher than in the business as usual scenario in 2050 (its growth rate remains above 3.5% throughout the simulation) and 14 million additional jobs have been created by 2050, while U.S. total energy demand is slightly lower than in the BAU scenario;
- Real disposable income per capita in 2050 is 32,000$ higher than in the business as usual scenario and government debt over GDP stabilizes at 1.48 instead of 2.2.

The analysis of the United States case study concludes that America needs (1) urgent new government regulations to mitigate energy consumption, (2) development and commercialization of new technologies to generate clean energy, and (3) improvement of energy efficiency and voluntary energy conservation.

However, because our analysis uses an integrated framework, it can and does point out the many unintended consequences of taking isolated steps instead of proposing a comprehensive energy package. These among others include increasing fuel consumption when CAFE standards are increased and higher emissions after 2020 when RPS are applied.

5.5 Sectoral Analysis: Transportation

There has been a long-standing perception among both the general public and policy makers that the goals of economic growth, environmental protection, national security and reduced oil use involve a complex set of trade-offs, one goal against another goal (Brown and Huntington, 2008; Howarth and Monahan, 1996). National defense goals are tightly coupled with climate change and with creating direct oil substitutes for liquid fuels (CNA, 2007).

This study was carried out to analyze whether a virtuous synergy arises from the expansion of electrified rail systems while shifting the national electrical generation towards renewables. Other oil mitigation proposals advocate expanding fossil fuel supply (Noriega, 2006) or using oil more efficiently. This study focuses on the proposal to create a parallel widespread multi-layer Non-Oil Transportation system[7] that would both conserve energy (using less energy much more efficiently) and substitutes fuel (using grid electricity). Nowadays, the U.S. transportation system is almost entirely oil based, at different levels of efficiency (Energy Security Leadership Council, 2006); currently, 0.19% of all U.S. electrical demand goes to transportation (EIA, 2007). National modal shares of electrified rail, bicycling and walking are minimal to trivial (Plaut, 2005). National security goals are also analyzed when simulating such a paradigm shift. Military uses of energy would benefit from less competition for oil from critical needs in the national economy in oil-constrained scenarios, as use of Non-Oil Transportation would be maximized. This was the national strategy during World War II. Lieut. E. L. Tennyson, Office of Chief of Transportation, U.S. Army, states that 90% of the 48 state ton-miles were by rail during World War II and trucks were used only when there was no rail alternative. Coal fired steam locomotives substituted for oil-based transportation during World War II. Electricity could substitute for oil in a future acute or chronic oil emergency.

The Threshold 21-USA model was employed to carry out the long-term analysis of the expansion of electrified rail as well as other policies. All scenarios simulated with T21-USA assumed a common oil constraint, based on the input of the Association for the Study of Peak Oil & Gas (ASPO), U.S. chapter, already

[7] Non-Oil Transportation System, as used in this study, does not include all forms of transportation that do not use oil, but only those with: a decreasing marginal cost of supply, high energy and economic efficiency, long replacement cycles (i.e. long lived infrastructure and capital equipment), and mature technology. The major modes that meet these criteria are electrified inter-city railroads, Urban Rail, bicycling (including electric assist) and walking. Secondary elements are electric trolley buses and Segways. Electric Vehicles met none of the criteria.

used in the T21-North America exercise (Wood et al., 2003; USGS 2000). The reference case is a market based approach, with prices as the primary driver of adaptation to shrinking oil supplies and no major changes in energy policy. As in the case of the North America study, this scenario is based on a market economy, where (1) Federal laws do not regulate electricity production from renewable energy sources, (2) there is no restriction on CO_2 emissions, and (3) heavy subsidies for ethanol are allocated as proposed by the United States Department of Agriculture (USDA) until 2016 (USDA, 2007). Alternative scenarios were added to the reference scenario. One scenario was a maximum push for electrified rail (i.e. Transportation), another was a major push for renewable energy (i.e. Renewable) and a third was the two combined.

The renewable energy scenario simulates large support for renewable energy, primarily electricity, by the Federal and State Governments. It assumed a Renewable Portfolio Standard (RPS) of 40% by 2025, increasing to 85% by 2035, is approved by the Government (as proposed by the American Council on Renewable Energy (ACORE, 2007)).

The Transportation scenario proposes the electrification of over 100,000 miles of existing inter-city railroads at Maximum Commercial Urgency (this should be interpreted as the maximum effort commercial firms will exert in pursuit of profits). These include 32,421 railroad miles that the Department of Defense has classified as being “strategic” (Military Traffic Management Command, 1998), 14,000 miles of grade separated three or four track service (comparable to CSX plans from Washington DC to Miami), with one or two tracks devoted to 100 to 110 mph passenger and express freight service, and electrification of upgrade of additional 60,000 miles. Such massive level of improvements would allow rail service quality to equal or surpass truck service in an oil constrained future. Given the cost advantages of electrified rail, this should allow for a projected 83% modal shift of the existing truck traffic to future rail.

The Urban Rail assumptions include an extremely aggressive increase in electrical demand by Urban Rail of 0.05% of total demand per year. This corresponds to a 28% annual increase in electrical demand, created by new urban rail lines, higher density on existing Urban Rail Lines and electrifying current diesel commuter lines. Existing Urban Rail systems can be enhanced for increased ridership at minimal cost (more rolling stock, greater crowding, etc.). However, massive annual gains in ridership (+28% of 2006 base) will require massive new construction. Assuming cost effective construction $60 billion (~$30 million/mile) appears to be a reasonable upper limit on annual investment. This translates into about 2,000 miles of Light Rail and streetcars per year (Rapid Rail being considerably more expensive and Regional Rail costs being highly variable).

Results show that these two combined investments of $1.7 Trillion over 20 years will create a 11% larger GDP, only 4% increase in Greenhouse Gas Emissions and a 26% reduction in oil consumption already in 2030 versus a strictly market based reaction. Adding renewable energy improved the results to GDP +13%, GHG -38% and oil consumption -22%.

More in details, when simulating the Transportation scenario in isolation, the electricity needed to power urban and freight rail increases from 0.0265 Quads (quadrillion Btu) in 2007 to 0.34 in 2025 and 0.43 in 2050, contributing to the growth of electricity demand (+7% in 2025 and +52% in 2050 with respect to the baseline scenario). Most of this increase would come from increased general economic activity and little from electrified rail. In fact, Real GDP at market price is projected to rise to $19.6 trillion in 2050 (+64% with respect to the reference case) in the Transportation scenarios, due to a reduced dependency on oil. This electricity, in the market base case, will generally be obtained by burning coal, the cheapest energy source for electricity generation. Though coal is less expensive than oil, its impact on the environment is a much more destructive. Emissions, in fact, increase to 4.7 billion tons in 2050 (-3% in 2025 and +24% in 2050 compared to the reference simulation), while coal consumption grows by 50% in 2050 with respect to the base case. When simulating the Transportation scenario, the average energy price declines and is constantly lower than in the Market Based case starting from 2020 and throughout the end of the simulation (-16% in the Transportation scenario and -18% when the renewable case is simulated, in 2050). The cost for the creation of an improved electrified rail sectors is estimated to amount about $1.7 trillion over the next 20 years. These combined investments represent 10% of GDP in 2007 and are lower than the projected avoided cost in 2030 already, that is they will have no net cost to the economy over a 20 years time frame. In addition, they are about 80% of total investment in 2007 or about 4% of the projected total investment, both private and public, for the period 2010 – 2030 (34% if only consider public investment).

When simulating the Renewable scenario in addition to the Transportation case, the increasing need for electricity is generated with renewable sources. The power generation from renewable sources equals 4,800 billion Kwh (a value 12 times higher than in 2007), representing 58% of total energy demand in the US in 2050 or 70% of 2007 demand. In fact, this simulation shows a considerable increase in electricity demand and a diversification of supply. As a consequence, electricity cost increases -both for the increasing demand and for the utilization of more expensive sources (+80% in 2050 with respect to the Reference case). The increase of electricity prices is a side effect that limits the expansion of electrified rail use, as shown by the decline in electricity demand for rail (-15% and -20% with respect to the transportation case in 2025 and 2050 respectively). Nevertheless, the high price paid for electricity, about $800 billion in constant 2000 USD (+25% with respect to the transportation case, or $150 billion) is generally offset by the savings generated by a reduced consumption of oil and more expensive fossil fuels as shown by a higher GDP (+75% in 2050 and +6% when simulating the Renewable scenario in isolation). Interestingly, this scenario also shows that a reduced consumption of coal for electricity generation in the US until 2030 will lower coal prices, leading to an increase in coal use by heavy manufacturing sectors, which is also coupled with lower oil use and higher GDP. Higher GDP though requires more electricity, which is mainly obtained by burning coal after the RPS goals are met after 2035. Policies aimed at reducing carbon emissions, such as the cap-and-trade proposals of US Senators Bingaman-Specter (S.1766) and Lieberman-Warner (S. 2191) would help reducing the come back of coal and the consequent increase in carbon and GHG emissions visible after 2035.

The combination of these scenarios shows how important well planned energy policies and synergies among the energy segments can be when facing challenges in both the energy and environmental sectors.

5.6 Sectoral Analysis: Energy Intensive Industries

The rising prospects that the U.S. Congress will enact climate change policies aimed at reducing carbon emissions over the next year or two has renewed worries about the potential impacts of energy price increases on manufacturing and the economy. Labor and many business leaders recognize that need to move forward in addressing the rising threat of global warming, and many support new policies that will limit carbon in the economy. At the same time, they want to ensure that these policies will not unfairly burden workers and businesses, or hurt the U.S. economy.

Specifically, this case study examines the impacts of energy price changes resulting from different carbon-pricing policies on the competitiveness of selected energy-intensive industries, especially in the face of international competition. It further examines possible industry responses, and identifies and provides a preliminary evaluation of potential opportunities to mitigate these impacts. The industry sectors investigated in the study—steel, aluminum, chemicals and paper—are among the largest industrial users of fossil fuels in the U.S. economy. The results of this examination, however, may also shed light on the implications of climate policies for other important energy-intensive sectors, such as cement and ceramics, and for manufacturing as a whole.

The main questions policy makers need to answer before committing to a specific policy intervention include:

- What climate policies are most effective at containing costs while reducing emissions?
- What policies can mitigate cost impacts?
- What policies promote and enable industry investments in new energy-saving technology?

In the present study these questions have been examined for a range of energy price increases associated with different climate proposals. In particular, the study compares the NCEP cap-and-trade proposal by U.S. Senators Jeff Bingaman (D-NM) and Arlen Specter (R-PA), the Low Carbon Economy Act of 2007 (S. 1766), at one end of the carbon-pricing spectrum, with variations of the Lieberman-Warner Climate Security Act of 2007 (S. 2191). The implications of other measures (e.g., allowance allocations, trade provisions, R&D investments) associated with these proposals also have been explored.

The research project involved developing detailed economic and energy profiles of these manufacturing industries, including the collection and processing of historical economic data, and construction of substantial industry sector models, supported by group model building sessions and numerous consultations with policy makers, experts and industry associations. Specifically, three are the main objectives of the modeling effort, supported by the data developed for the industry profiles: (1) model the production cost structures for each industry, and assess the impacts of carbon pricing policies on these costs, (2) model the market dynamics for each sector, and assess the consequences of production cost increases on the sectors' profitability, production output and market share, in the face of international competition, which can constrain manufacturers' ability to pass costs along to consumers, and (3) identify, model and evaluate the range of investment options—from capacity changes (including cutbacks and offshoring) to new energy and labor productivity enhancing technologies—available in each sector and the likely industry investment choices under different policy scenarios. To characterize the two different policies (S. 1766 and S. 2191), the Energy Information Administration's (EIA) National Energy Modeling System -NEMS (EIA, 2003) has been used to generate price projections for several different energy sources up through 2030.

A primary objective of the study was to compare the effectiveness of alternative policies for containing the cost impacts on these sectors from climate regulations, while still promoting the environmental goal of reducing GHG emissions. The Bingaman-Specter proposal is presumed to have the strongest cost containment measures among the three policy cases we examine—in particular, its "technology accelerator payment" (TAP). The Lieberman-Warner Core legislation lacks direct cost containment features, though its international offsets provision appears to have the affect of slowing cost increases. A Lieberman-Warner No International Offsets case was then included, which assumes that international offsets allowed in the Lieberman-Warner Core legislation are severely limited by cost or regulation. The EIA notes in its analysis of the Lieberman-Warner bill, that the regulations that would "*govern the use of offsets have yet to be developed and their availability will depend on actions taken in the United States and around the world.*" (EIA, 2008). Therefore, the model simulations of the no offsets case, which reflects a condition of little or no cost containment, may approximate a more realistic outcome that policymakers will need to consider if the Lieberman-Warner bill was actually enacted and implemented.

The results of the simulation indicate that each climate policy will impose higher energy costs to the manufacturing sector. Higher energy prices will be reflected in higher production costs and lower profits in the medium and longer term. Some energy industries result to be more vulnerable than others to increasing energy prices. The greatest impacts on production costs are on iron and steel (6-18%), chlor-alkali (4-17%), followed by paper (2-9%) by 2030. Aluminum and petrochemicals have somewhat smaller increases, due to smaller consumption of carbon intensive energy sources, but still could be troubling. Similarly, all industries suffer operating surplus/profit losses, but some more than others. Steel, chlor-alkali and paper show the heaviest losses; primary aluminum moderate losses; petrochemicals, secondary aluminum, small losses. In this respect, defining cost containment features as well as mitigating and offsetting increasing energy costs through efficiency gains have emerged from the current policy debate as effective measures to soften eventual pressures on steel, chlor-alkali, paper and perhaps primary aluminum to cut capacity.

Results of the simulation show that the "cost containment" feature included in some policy proposals helps reducing the impact of the climate policies considered: S. 1766 has much more modest impact than S. 2191, while the simulation of S. 2191 with no international offsets has an impact somewhat higher on all industries. On the other hand, the results of the analysis clearly show that the allocation of international offsets and the introduction of cost containment features only delay the cost pressures observed in the S. 2191 case, creating bigger longer term problems (towards 2030) when energy prices will be higher than in the period 2012-2020. Cost containment measures and the allocation of offsets therefore do not solve problems created by increasing energy costs; furthermore, they postpone cost pressure to a time when it will be more difficult to find longer term solutions to it.

Large efficiency gains are required to offset losses related to the implementation of moderate and high-CO2 prices. In the iron and steel industry, S. 2191 case, needed efficiency gains are in the range of 53% in fuel use, 62% in energy feedstock consumption, and 12% in electricity in 2030 (in the S.1766 case these would be 34%, 44% and 7% respectively). According to the IEA and industry representatives, technological options exist, but are limited, expensive and may not be available soon. Nevertheless, the average potential avoided cost for the iron and steel industry is estimated to be around $7.5 billion per year (real USD) for the period 2012/2030 in the S. 2191 case and $3 billion per year in the S. 1766 scenario. Results of the simulation show that investing early in energy efficiency (to the extent possible according to the technological options made available to the various industries) will save money, mitigate the impact of the implementation of climate change policies, and increase the medium and longer term competitiveness of energy intensive industries.

Regarding the impacts of international competition, the possibility to pass the cost along to the market will play a determinant role on the competitiveness and profitability of U.S. energy intensive manufacturing sectors. In fact, producers are likely to be facing a dilemma soon: if they decide to pass-along the domestically induced increase in energy cost to the market, their market share is likely to decline, while their revenues and profits may remain somewhat constant depending on their vulnerability to international competition. On the other hand, if domestic producers to do not intend to face the risk of reducing production capacity to keep high revenues and profits, they can decide not to pass the cost through. In such a scenario, their market share and revenues are likely to remain constant (all else equal), while their operating surplus and profit margin with shrink. In other words, companies will have to decide whether to maximize profits or strengthening their position in the market.

6. Insights from case studies

The analysis carried out with the case studies helps estimating what the value added of performing a context-wide integrated analysis with System Dynamics is. When studying complex systems, many factors influencing their behavior should be taken into account. These can be represented as exogenous variables or explicitly modeled through the representation of feedbacks, nonlinearity and delays. System Dynamics allows for the incorporation of energy and society, economy and the environment into one flexible and transparent framework, in which the underlying causal structure of the system analyzed is represented. Results of the case studies both confirm expectations and widen the analysis, and show the existence of policy resistance mechanisms, providing insights on the causes for side effect to emerge, both into the medium and longer term. The main results of analysis of the five case studies proposed include:

- Ecuador: Investing one percent of GDP into energy efficiency does not help the Republic of Ecuador reducing CO_2 emissions below current levels. Nevertheless, it reduces energy consumption and allows GDP to grow faster. On the other hand, higher economic activity translates into increasing energy demand, which makes so that the targets for emissions reductions will be even more difficult in the future. Similarly, reinvesting avoided energy cost into social services helps reducing poverty but increases resources of low-income families, which may spend more for energy consumption.
- North America: Implementing policies currently being debated does not help mitigating the impact of peak oil, especially if timely actions are not taken. The effect of higher energy prices will ripple throughout the economy impacting all major actors: households, producers, government and banks. The goal of high longer term economic growth translates into higher energy demand and, with decreasing EROI, finding an equilibrium will becomes more and more difficult over time. Subsidies on ethanol, among other policies, may not generate the

expected advantages. Actually, the production of first generation corn ethanol will put enormous pressure on water demand and land allocation, with corn export (which is usually directed toward developing countries) reaching negative territory before 2015.

- United States: Increasing fuel efficiency of passenger vehicles (CAFE) and diversifying the energy supply mix by increasing renewable energy production (RPS) are good strategies to reduce dependence on oil in the medium term. Furthermore, the study highlights that RPS may not have a negative impact on the economy, creating instead jobs and having little impact on electricity prices. On the other hand, the rebound effect for CAFE at the macroeconomic level may reduce the expected effectiveness of this intervention, generating higher energy demand when CAFE standards are implemented in isolation. Setting challenging goals for RPS in the medium term and reducing the effort over the longer term may have serious negative impacts on the economy and emissions. The former relates to boom and bust cycles in the renewable energy sectors, the latter refers to the fact that (1) reducing oil consumption increase GDP as well as energy demand and that (2) reducing coal consumption and its price, will benefit heavy manufacturing industries and disadvantage emissions reduction goals.
- Transportation: This case study shows that a reasonable investment in known urban and freight rail technology can substantially support the United States moving towards reducing oil dependence. This intervention would allow GDP to grow faster, improve national security and limit the projected increase of emissions. In order to reduce emissions instead, a synergy can be found in increasing renewable energy production. There are side effects emerging from this synergy though: higher electricity generation from renewable sources would reduce coal consumption (of which the United States have abundant reserves) as well as its price, in absence of carbon policies. Such development would help

U.S. energy intensive industries become more competitive, at least for a few years. In fact, the declining effort in pushing renewable energy production as part of RPS proposed legislations (or driven by the fact that only a limited portion of energy consumption can be generated with non-thermal processes), will make so that coal will have to be used to supply higher and growing demand for electricity. This, in turn, will increase coal prices, pressing energy intensive industries to reduce their energy consumption when such a change may be more costly.

- Energy intensive industries: The study of the competitiveness of energy intensive U.S. manufacturing sectors reveals that most if not all industries will be affected by policy induced increasing energy prices, especially those consuming carbon intensive energy sources (both as feedstock or for direct use). Options, though not trivial, are available to counter reductions in revenues and profits: investing in energy efficiency or passing the cost through to the market. The analysis of the former shows that acting early helps mitigating the impact of carbon policies and provides, at the cost of an upfront investment, longer term competitive advantages and better economic results. The latter is more of a dilemma for producers: if they do not pass the cost through, profits will shrink and the market share will remain stable; on the other hand, if they do pass costs along, revenues and profits will stay somewhat constant and their market share will decrease. Other features of policies, such as cost containment and international offsets do not represent longer term solutions, as they may only delay the investment decision to a later time, when solutions will be harder to find and actions will be more costly due to even higher energy prices.

These results show the presence of side effects or unintended consequences arising in the medium to longer term from within the energy sector and influencing both the same sector (e.g. applying Federal RPS mandates may reduce coal price and increase industry's consumption of coal coke and synthetic fuel) as well as society, economy and environment (e.g. electrifying rail and increasing renewable energy production generate stronger economic growth and contain emissions, while a synergetic carbon policy can be implemented to reduce the consumption of carbon intensive fuels and preserve the environment). While the use of conventional models do not allow for it, these results are obtained through the simulation of integrated frameworks in which indicators for energy, society, economy and environment are interconnected and endogenously calculated. These four "spheres" and the representation of feedback, nonlinearity and delays, together with the utilization of a participatory and transparent approach, contribute to the representation and understanding of the context (social, economic, environmental and political) in which issues arise and within policies are formulated and implemented.

The tools used in the present research work, based on System Dynamics and borrowing from other methodologies, allow for building on -and expanding- other research by incorporating it into a coherent framework and generating new insights. These include an integrated analysis of the impacts of (1) increasing energy efficiency to reinvest the avoided costs in social services in developing countries, which would not be possible when using exogenous inputs for key variables such as GDP and population; the event of peak oil on (2) emissions, (3) the economy and on (4) the Energy Return on Investment (EROI), for which dynamic scenarios linking energy to society, economy and the environment have to be used to fully understand cross sectoral reactions to increasing energy prices, e.g. economic growth and energy demand, as well as energy supply choices and their impacts on land use and emissions.

In addition, this research contributes to the study of more detailed cross-sectoral effects of:

(5) Improved CAFE standards on the economy (i.e. rebound effect, see Dimitropoulos, 2007). Customer responses as well as economic scenarios are

jointly used to understand the wider implications of the rebound effect on the effectiveness of increasing fuel efficiency standards;

(6) Renewable Portfolio Standards. Entails the need to investigate the broader relations between energy and the economy requiring a sectoral as well as a macroeconomic study;

(7) Cap-and-trade proposals. Involves the detailed analysis of energy intensive industries, including researching the impact of climate policies on production costs, international competition and technology options on top of the evaluation of the effectiveness of such policies in reducing emissions and while supporting the creation of employment and economic expansion.

(8) Investments in electrifying rail while (9) increasing the understanding of whether national security and climate strategies are compatible and complementary. Requires the use of an integrated approach that allows to estimate the impacts of investments in the public and freight transportation sectors, on society (e.g. TOD), the economy (e.g. GDP) and environment (e.g. emissions), as well as on energy (e.g. oil consumption) and national security (e.g. dependence on foreign sources of oil).

(10) Subsidies to ethanol and (11) their contribution to the transportation sector. A longer term analysis of the impacts of crop use for fuel production requires the study of land, and water requirements as well as the use of fertilizers, which influence the net energy contribution of ethanol (EROI) to the transportation sector.

As previously mentioned, the methodology adopted allows for a transparent representation of reality, supporting the creation of knowledge and the establishment of a relationship based on mutual trust with policy makers and stakeholders. Among others, this is built upon the fact that users of the models, stakeholders and policy makers can test the consistency of data and assumptions provided by different agencies. Scenarios can be simulated on the fly, using a flexible and transparent framework, to obtain a variety of coherent results that serve as the basis for an effective and insightful conversation. Such characteristics of the approach proposed made so that policy makers and stakeholders were able to learn more about the dynamic complexity of the system during group modeling sessions and presentations, and were able to provide useful insights for the development of the models.

7. Conclusions

With the adoption of the Kyoto Protocol (UN, 1997) in 1997, national leaders have started investigating options for reducing carbon emissions within national borders. After ten years debating on 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.

The main motivation for the present study stems from the acknowledgement that there is a need for integrated tools 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).

The present study aims at evaluating whether energy issues should be contextualized to effectively support policy formulation and evaluation. 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. While the analysis carried out with conventional linear programming and optimization models is limited by narrow boundaries and lack of dynamics, computer simulation models based on System Dynamics can effectively support the analysis of both context and policies.

The present research work proposes the utilization of integrated energy models based on Millennium Institute's Threshold 21 (T21) and Minimum Country Model (MCM). The use of these tools supports the current research work by providing an integrated analysis of the following characteristics of the policy-making environment:

- In spite of energy issues being global, regional and national, policy solutions are designed and implemented at the national level.
- Despite interconnected and cross-sectoral energy issues, policies are narrowly focused on the energy sector while having an impact on society, economy and environment.
- 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.

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.

Results of the research work carried out with five case studies, focused on the simulation of various energy and climate policy options, indicate the likely emergence of various unexpected side effects and elements of policy resistance over the medium and longer term, due to the interrelations existing between energy and society, economy and environment. Furthermore, side effects or unintended consequences may arise both within the energy sector and in the other spheres of the model; nevertheless, these behavioral changes influence all society, economy and environment spheres.

The endogenous simulation of the causal relations underlying the structure of the system is responsible for the generation of side effect and unintended consequences. Feedback loops, nonlinearity, and delays are explicitly represented in the model proposed, especially when linking energy, society, economy and environment. This representation of the context, coupled with the understanding of the political dimensions -during the modeling process-, allows a better understanding of the functioning mechanisms driving the behavior of the systems analyzed, making possible the identification of structural changes (i.e. loop dominance) responsible for behavioral changes.

Further research work is needed to better evaluate whether representing the context can significantly change policy analysis carried out with simulation models. Three main areas for further work are identified:

- Methodology: more work should be devoted to the analysis of how the System Dynamics approach and models can contribute to the analysis carried out with optimization and econometric models, and complement it. A variety of policy-related studies are becoming available and a direct assessment of the potential synergies existing among models and methodologies seems achievable (an example exist in the Stanford Energy Modeling Forum).
- Model: the relevance of the context should be analyzed for more case studies, both for detailed and broader issues. In addition, the boundaries of the models proposed in the present research work can be widened to include a variety of feedback loops that were not analyzed at this stage. These include the impact of water pollution when producing unconventional oil, the macro effect of biofuels production on food prices and poverty, etc.
- Dialogue: there is a need continue and further develop the dialogue with policy makers, focusing on the understanding of assumptions and key structural relations used in the model. The ultimate goal should be to build a relationship of mutual trusts, asking the right questions and proposing good stories and insights.

Despite the fact that models are not, and will never be, perfect representations of reality, this research work argues that explicitly representing the context in which

energy issues arise, and where policies are formulated and implemented, enriches the analysis of energy policies and provides useful insights to policy makers. The present study proposed the utilization of an integrated cross-sectoral medium to longer-term research approach, complementary with other tools and methodologies, in which integrated models are used to minimize exogenous assumptions by endogenizing key variables to increase coherence of scenarios and improve the understanding of the system. This approach includes also an active involvement of policy makers and stakeholders, aimed at creating a relationship of mutual trust to maximize the effectiveness and validity of the models used by correctly understanding and incorporating the political context.
By doing so, the context, built into an integrated model, becomes a fundamental driver in the modeling process and completes the analysis of energy policy formulation and evaluation.

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US Congress H.R. 969: To amend title VI of the Public Utility Regulatory Policies Act of 1978 to establish a Federal renewable energy portfolio standard for certain retail electric utilities, and for other purposes.

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Appendix A: T21 Models Performance

This section provides an overview of the performance of T21 models created by the Millennium Institute over the last 10 year. This analysis serves to provide an indication of the reliability and validity of projections simulated with T21, using causal relations, feedback, nonlinearity and delays, as the main pillars of the model.

T21-Malawi, 1997

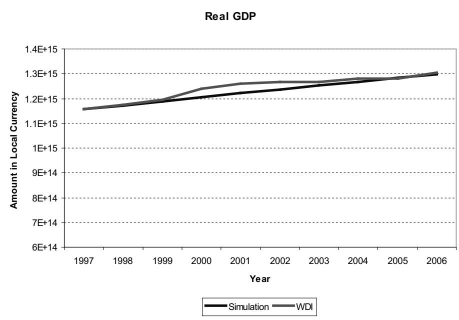
In 1997, MI developed a T21 model for Malawi to help its government translate the *Vision 2020* goals into measurable objectives through national stakeholder consultations and analysis of scenarios. The outcome was a new national development strategy, *Reaching the Vision* that sets out the path to attaining the national vision.

For past projections, the model performs well for total population with an average deviation smaller than 5% from UNPOP and WDI values. For real GDP, the dips in 1992 and 1994 are caused by severe droughts that occurred in Malawi and the model didn't predict.

For 1998-2006, the total population still stays within 5% and for GDP, the model is able to reproduce their medium to longer term quite well, but underestimates growth after 2001.

T21-Italy, 1998

In 1998, under a contract with ANPA, Italy's National Agency for the Protection of the Environment, and with collaboration from ENEA, the Italian Department for New Technology, Energy, and the Environment, MI customized the T21 template model to Italy and began an exploration of how best Italy could achieve its various international environmental commitments. The goal was to find scenarios under which Italy could achieve its commitments without doing serious damage to its economy.

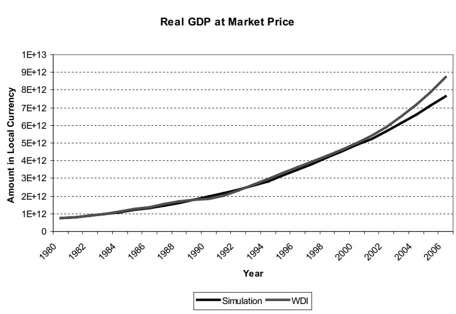


The Italy model performs very well against actual data. For past projections, total population has an average deviation of 2% and Real GDP is about exactly the same as WDI.

For 1999-2006, total population remains within 2% until 2003 and after that is still 4-5%. The Real GDP remains about 4% throughout, becoming better over time.

T21-China, 2002

In 2002, General Motors supported the development of T21-China for highlighting China's growing energy and food demand.



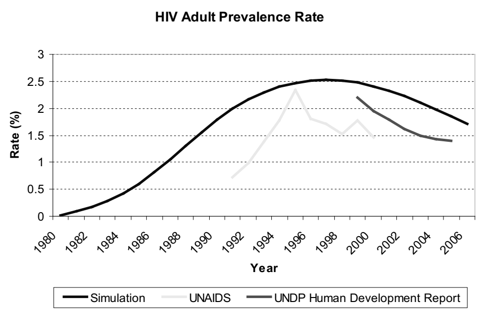
The T21-China model performs very well when compared against the actual data. For past projections, the values are within 2% for total population and Real GDP varies between 2-4%.

For 2003-2006, total population also has an average deviation of only 2% and for Real GDP the model underestimates the economic growth driven by government actions not accounted for when building the model.

T21-Thailand, 2002

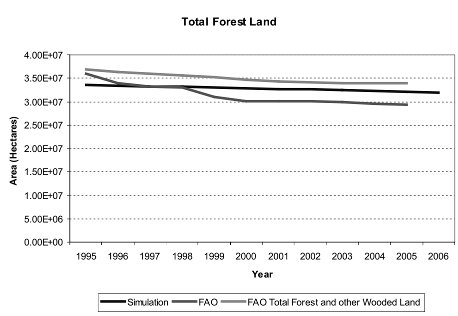
In 2002, MI created the T21-Thailand model to look at population, reproductive health, and HIV/AIDS.

In terms of past and future projection, total population has an average deviation of only about 2%. The simulation of the HIV Adult Prevalence Rate has a difference of only about 0.2% both past and future, but captures the longer-term trend pretty well, especially considering the inconsistencies in UNDP and UNAIDS data.



T21-Papua, 2002

In 2002, Conservation International and MI collaborated on pursuing a more cooperative approach to address the concerns of various interest groups represented in Papua's environmental and economic resources to create T21-Papua: A new approach to integrating development planning with biodiversity conservation.



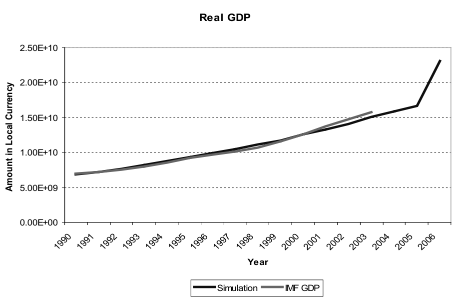
For past projection, both population and Real GDP fall within 5% of actual data. For 2003-2006, population remains within 5% but for Real GDP a spike occurs in 2004.

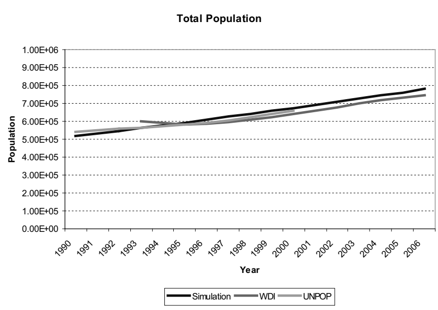
As for total forest land, the model performs very well both past and future in spite of a change in classification methods at FAO. As a consequence, the simulation is consistently about 5% lower than Total Forest and Wooded land, but 5% higher than Total Forest Land, perfectly matching the long term trend.

T21-Bhutan, 2002

In 2002, MI and the Government of Bhutan (GoB) collaborated to create a T21 model. In 2004, as part of the Netherlands Climate Change Studies Assistance Program, the GoB decided to use T21 to investigate impacts of climate change on Bhutan.

For past projection, the model accurately simulates the trend of total population and GDP falls within 5%. For 2003-2006, total population continues to represent



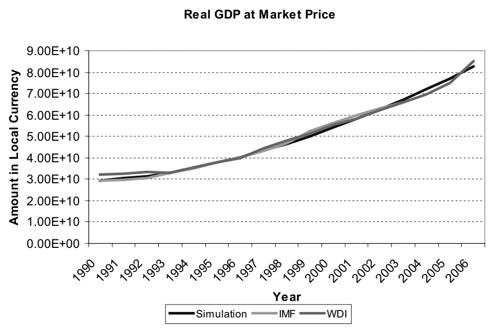


the trend in WDI and UNPOP data and for GDP, the rapid increase in 2006 is due to the completion of a major hydroelectric plant.

T21-Cape Verde, 2003

In 2003, Senior Cape Verdean government officials identified T21 as an excellent tool to assist in undertaking integrated strategic planning, involving diverse stakeholders in the planning process, and monitoring performance against agreed goals. MI developed T21 Cape Verde specifically to support the Poverty Reduction Strategy Paper (PRSP) process.

In terms of past projection, for total population there is an average deviation of 3% with UNPOP data and for Real GDP, it is also only 3% from IMF and WDI data as shown.

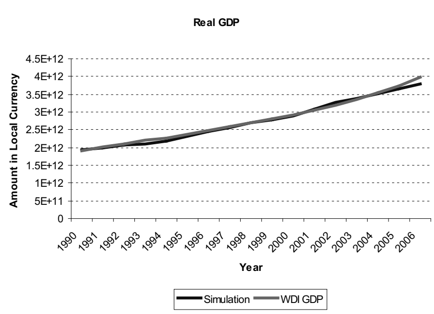


For 2004-2006, the total population is now within 5% of actual data and Real GDP remains within 3% of WDI data.

T21-Ghana, 2003

In 2003, MI created T21-Ghana (*Assessing best options for meeting the Millennium Development Goals in Ghana*) in order to assess the impact of MDG-related interventions on the national economic and social development, and the synergies (or lack thereof) among them.

In terms of past projection, for total population there is an average deviation of only 2% from UNPOP and WDI data and for Real GDP, the projection falls to within 3%.

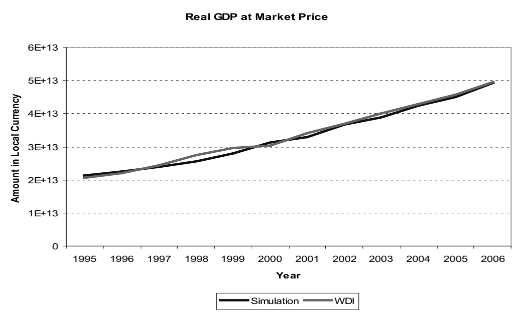


For 2004-2006, population is within a maximum of 3% and GDP a maximum of 4%.

T21-Mozambique, 2003

In 2003, MI worked with Mozambique's government ministries and civil society groups to build their capacity to use T21, and use it as a framework for broad dialogue on policy issues, thus increasing broad participation in national planning.

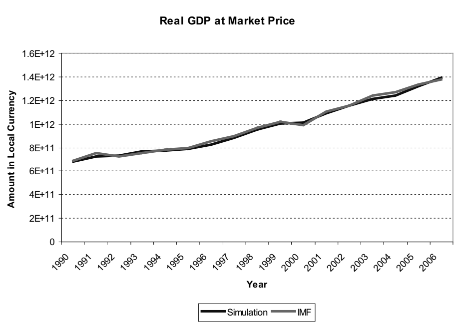
For past projection, the total population falls to within 4% of UNPOP and WDI measures and the Real GDP varies a bit but is mostly within 4% of actual data.



For 2004-2006, population has a deviation of between 4-5% and GDP falls consistently within 2-3% of actual data.

T21-Mali, 2003

In 2003, under The Carter Center's Development and Cooperation Initiative (DACI) with the Government of Mali, MI used T21 to support the preparation of Mali's poverty reduction strategy paper for the World Bank (PRSP).

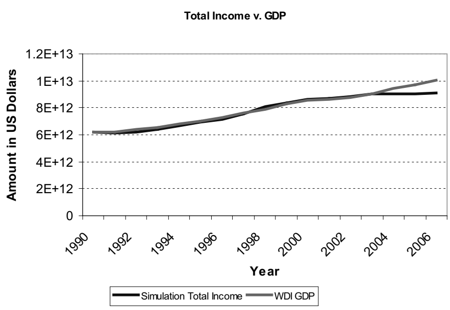


In terms of past projection, for population there is an average deviation no more than 3% for both WDI and UN data and for Real GDP there is variation, though it follows a similar trend and is usually within 5% of WDI data.

For 2004-2006, population has 4% average deviation while GDP is within 3% of actual data.

T21-USA, 2004

The second version of the model for the United States, which focused on the economic sector and was created and featured on C-SPAN, overall performs very well on the major indicators.

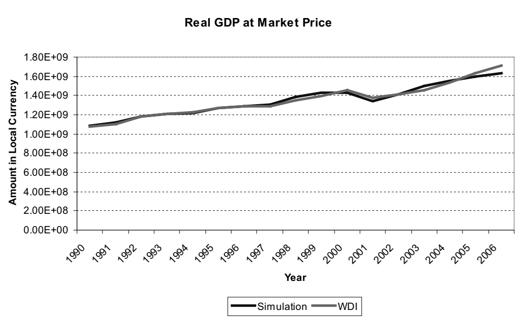


For past projections, the total population falls to within 3% of UNPOP and WDI, total real trust funds have a average deviation of about 4%, and Real GDP has an average deviation of just 3%.

For 2005-2006, population remains within 3%, total real trust funds goes up to around 5%, and a spike for Real GDP occurs in 2003 due to the economic and monetary policies of the second Bush administration that have stimulated the financial sector and housing market more than expected.

T21-St. Lucia, 2004

T21-St. Lucia is a simplified T21 model that was developed to support a training program on integrated development planning conducted in the country in 2004.



For past projects, total population falls to within 1-2% of WDI data and Real GDP is within 2-3% of WDI data, while keeping in line with fluctuations that can occur but are difficult to account for.

For 2005-2006, the population has an average deviation of 3% from the WDI data and the Real GDP is within 4% of WDI data.

B

Appendix B: Baseline USA Scenario and Comparison of Results

T21-USA is an integrated model created to support policy formulation and evaluation. Its structure is based on four spheres: society, economy, environment, and energy. T21 has been customized to the United States to address a set of energy-related issues in a broader context, and its structure is enriched with numerous relations between conventional energy sectors and the environmental, social, and economic spheres. Projections were completed at the end of 2007.

This appendix provides a more comprehensive description of the business as usual scenario simulated with T21-USA and a comparison with the EIA Annual Energy Outlook 2007 (EIA, 2007). T21-USA and the AEO 2007 have been chosen for their similar boundaries of analysis and business as usual assumptions.

The behavior description and comparison of the business as usual (BAU) scenario of T21-USA concentrate on energy and its interconnections with the three spheres of society, economy and environment. Furthermore, given the dynamic nature of the model and the numerous feedback loops existing among these spheres in the model, results and projections generated by T21-USA are shown within each sphere.

The results produced by the interconnection of society, economy, environment, and energy are presented graphically for the period 1980 – 2050. The simulated behavior of the model is compared to historical data (1980 – 2006) and then projected until 2050. The first 25 years of simulation contribute to the validation of the model. In fact, the structure of the model, representing causal relationships underlying the systemic analysis, should produce a consistent behavior over the past in order to generate reasonable projections for the future. If past behavior as represented in the model does not reasonably match historical data, then it might be that some important feedback loops -the core logic structures of the model- are missing. This simulation of history significantly helps improve the structural analysis of the model (Barlas, 1996; Sterman, 2000).

Business as Usual Scenario (BAU)

The business as usual (BAU) scenario relies on the assumption that current trends will continue. Efficiency of vehicles and average miles yearly driven per vehicle follow the historical trend (1980 to 2006) assuming that the CAFE standard will not be modified. An alternative scenario examines the proposal to set CAFE to 35 mpg by 2020 (H.R. 1506), which was incorporated in the H.R. 6. Similarly, in the business as usual scenario, no extraordinary improvement in energy efficiency (end-use technology) is assumed to take place by 2050 (endogenous calculation sets improvement at about 47%, or about 0.9% per year), overproduction does not generate losses of oil reserves, and there is no extraordinary addition to known oil resource or reserves globally. According to historical evidence found in the case of USA petroleum production (Yergin, 1991), cutting edge oil recovery technology can be developed during peak production years. On the other hand, since exploration activity did not lead to large discoveries in the USA after petroleum production had peaked in the USA (Hall et al. 1986), exploration technology is assumed to develop at a normal pace (i.e. endogenously calculated). Nuclear power and renewable energy generation from wind, solar, geothermal, hydro and biomass follow the latest projections of the Energy Information Administration (EIA, 2007). Their production cost decreases by 15% between 2006 and 2050. Total USA and World original oil-in-place (i.e. total resource base without regard to recoverability) are set to 650 billion and 4.9 trillion barrels, respectively. Substitutes for oil (e.g. biofuels, biodiesel, alcohol fuel) are assumed to be available and produced starting from 2006, with a 5-year delay between investment and full capacity in place. Their price is assumed to be constant and equal to $100/barrel. Further work will include technology improvement and cost abatement. The taxation of both gasoline and income is projected to follow the historical trend observed in the period 1980 – 2006, therefore income taxation will slightly increase after 2007. Public expenditure is assumed to be proportional to GDP, generating a public debt in the middle range of the Government Accountability Office projections (GAO, 2006). The GDP growth of China and India is projected to decrease linearly to reach 2 and 3% respectively by 2050.

Table 1: Main exogenous factors defining the Business ad Usual Scenario

	2006	2030	2050
Fuel Economy (miles per gallon)	17.0	18.0	18.8
Miles Driven per Vehicle per Year (miles per vehicle per year)	12,400	13,800	14,000
Oil Recovery Technology Enhancement	Up to 35%, depending on the demand/supply balance		
Energy Consumption Technology Enhancement	_	_	_
Overproduction Effect on Oil Fraction Recoverable	–	–	–
Net Change in Undiscovered Resource	_	_	_
Net Change in Discovered Reserve	_	_	_
Gasoline Tax (as percentage of Gasoline price) (in cents/gallon)	18.8% 35	11.0% 70	14.2% 100
Income Tax (as percentage of GDP)	12.0%	14.4%	13.9%
Biofuel Price (real USD per barrel)	100	100	100
Nuclear Energy Production (Billion Kilowatt Hour -Bkwh- per year)	778	870	1195
Wind Energy Production (Bkwh per year)	25.8	51.8	52.2
Solar Energy Production (Bkwh per year)	0.77	2.41	3.65

Behavior of the Social Sphere

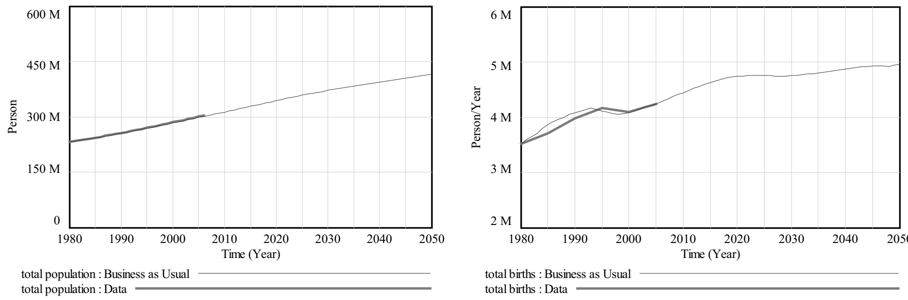
The main outputs of the Social Sectors in T21-USA are population, its distribution into age cohorts, and life expectancy. These main endogenous factors affect population development, together with income (Shorter et al., 1995). Total labor supply is generated, a social indicator highly dependent on population and influencing employment and labor cost. The latter affects labor-related technology development and therefore total labor demand, which is one of the main factors behind employment dynamics.

Population

Projected total population is shown in Figure 1a. Historical data, represented by the red line, are taken from the United Nations Population Division (UN, 2007). Total population in the USA is projected to grow by 38% in the period 2006 – 2050, reaching 414.5 million people. Population growth in the US, especially for the elderly age cohorts, is likely to affect the sustainability of social security and medicare trust funds. In this regard, various policy options can be tested with the model.

Births are based on fertility (exogenously calculated) and income levels. Deaths are influenced by life expectancy. The main factors responsible for a change in life expectancy in T21-USA are income and the effect of fossil fuel emissions. The relationship between fossil fuel emissions per hectare of land (CO_2 emissions per hectare is assumed to be a good proxy for PM10 concentration) and mortality has been estimated based on data from a study by AEA Technology Environment, commissioned by the European Commission, Clean Air for Europe -CAFE- Program in 2005 (AEA Technology Environment, 2005).

Figure 1a and b: Comparing total population and births in T21-USA to historical data



Population pyramid

The population pyramid is calculated by grouping one-year age cohorts into five-year cohorts. Births and deaths per each age cohort are endogenously calculated and an aging chain determines the shift from one cohort to the next each year. Total population results from the sum of all the age cohorts, both for male and female subgroups.

Four population pyramids are shown below: 1980, 2000, 2020 and 2040 respectively. By looking at them, it is clear that the population groups aged 65 and older will increase faster than the average total population. In particular, two population waves are evident in the medium term and contribute to the growth of the elderly population. The first one, known as the ‘baby boomers’, is clearly visible in the pyramid for 1980 (age 10 to 34) and 2000 (age 30 to 54), while the second one is observable in the pyramid for 2000 (age 0 to 19) and 2020 (age 20 to 39). The accumulation of these two waves, coupled with the improvement of health conditions and, consequently, life expectancy, is the main driver of the elderly population growth in the USA.

Figure 2a and b: Comparing population pyramid in T21-USA to historical data (1980 – 2000)

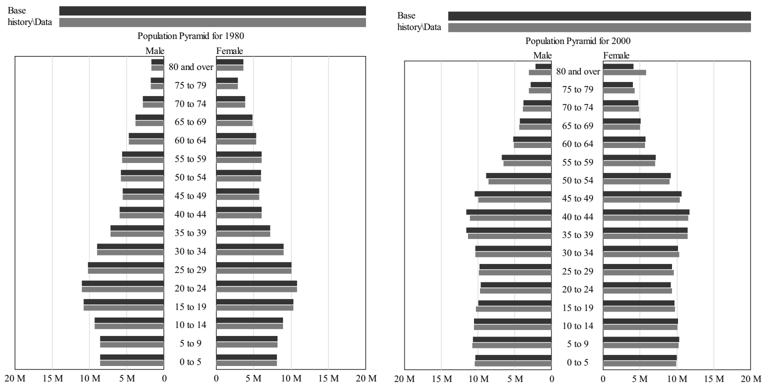
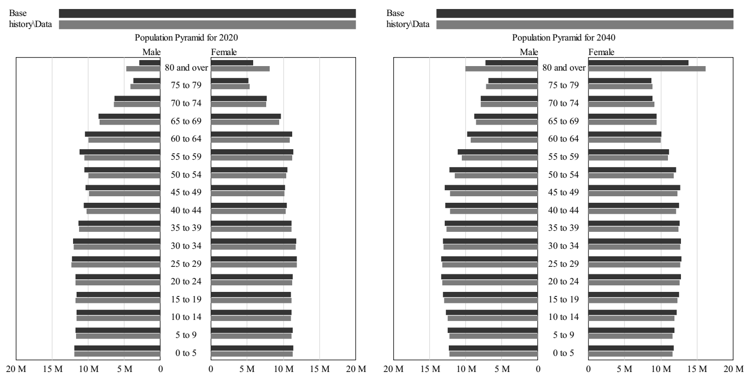


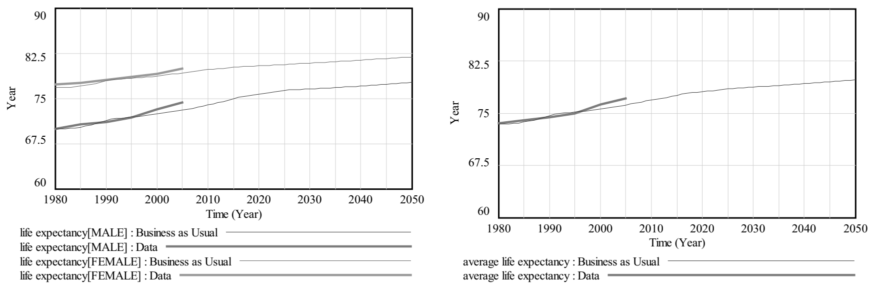
Figure 3a and b: Comparing population pyramid in T21-USA to U.N. projections (2020 – 2040)



Life Expectancy

The development of life expectancy (LE) in the model is mainly endogenously influenced by per capita income. LE is projected to grow from 79.5 years in 2006 to 82 in 2050 for females, and from 73.5 years in 2005 to 77.5 in 2050 for males.

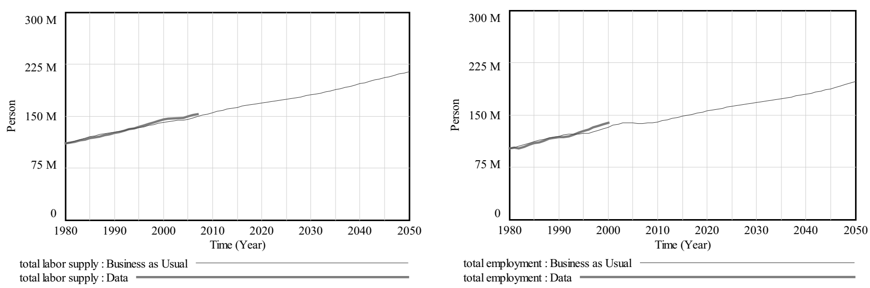
Figure 4a and b: Comparing life expectancy in T21-USA to historical data



Labor Supply and Employment

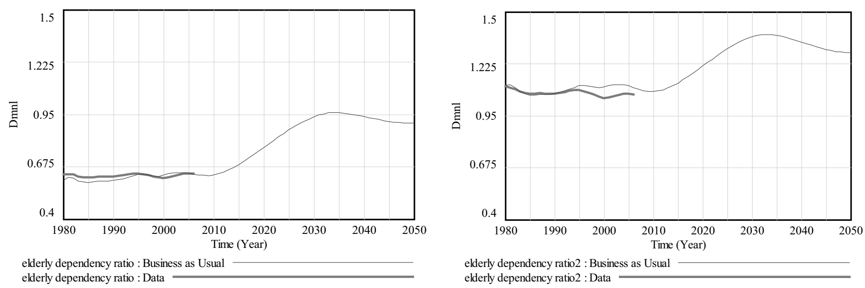
Labor supply and employment are both projected to increase, in line with the positive trend observed since 1980. Simulated labor supply increases by 45% (reaching 213.5 million) during the period 2006 – 2050, with employment rising by 43.5% to 198 million.

Figure 5a and b: Comparing labor supply and total employment in T21-USA to historical data



The elderly dependency ratio is shown in Fig. 6a and b. The former is calculated as social security and medicare beneficiaries, over workforce. The latter is equal to social security and medicare beneficiaries plus population younger than 16, divided by the workforce. Both increase over time, reaching respectively 0.9 (from 0.64 in 2006) and 1.26 (from 1 in 2006) by 2050.

Figure 6a and b: Comparing dependency ratios (elderly -10a- and elderly plus youth -10b-) in T21-USA to historical data

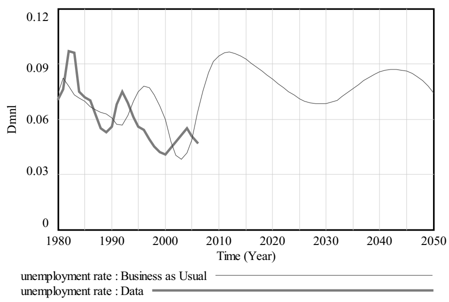


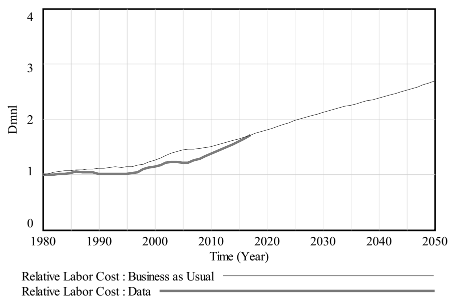
Unemployment

The unemployment rate shows an interesting pattern of behavior. Oscillations are clearly visible in both historical and simulated values, but magnitude and cycles (influenced by delays) do not always correspond. The unemployment rate changes from 6% in 2006 to 7.3% in 2050, due to the ageing of the two population waves described above and to the effect of the energy transition on the labor market and GDP. The latter consists in a faster economic growth due to the shift towards renewable power generation and alternative forms of energy. New investments in the energy sector generate employment opportunities. In addition, decreasing energy prices stimulate growth. Both these factors make unemployment decrease when the transition beyond oil takes place.

Even though the projection indicates a decreasing unemployment rate for the years to come (i.e. 2010 to 2030), a breakthrough with innovation in labor technology and increased immigration could still augment it. Simulating alternative policies and assumptions can help test the effect of these factors on unemployment rate.

Figure 7a and b: Comparing unemployment rate and labor cost in T21-USA to historical data





Behavior of the Economic Sphere

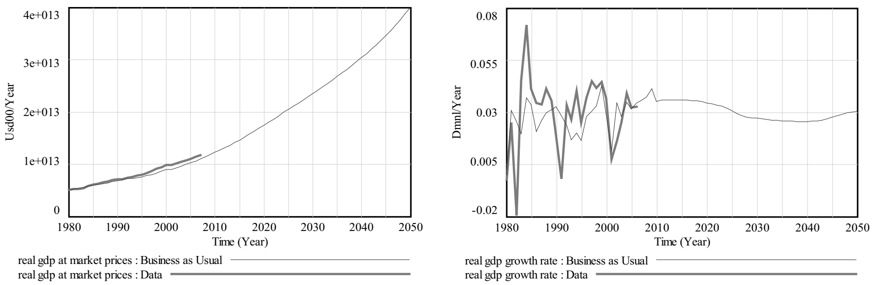
The main components of the Economic Sectors included in T21-USA are related to the four agents acting in the USA economy: producers, government, households, and the rest of the world (ROW) (Drud et al., 1986). A few indicators are shown per each agent:

- Producers: production (GDP) and its components (agriculture, industry and services);
- Government: revenues, expenditure, investment, debt, and trust funds;
- Households: private investment, per capita disposable income, and propensity to save;
- ROW: balance of payments, trade balance, and net services.

Producers

Real GDP at market price is projected to become four times as high in 2050 as in 2006, reaching 40 trillion USD (using 2000 as the constant dollar base year). Among sectors, agriculture is projected to grow by 86%, industry by 128%, and services by 325%. The share of each sector in GDP is as follows: agriculture, which accounted for 1.5% in 2006, is projected to decrease to 0.75% by 2050; industry's share declines from 24% to 14.25%; and services' portion increases from 74.5% to 85%. In the economic sectors of T21-USA, historical comparison is mainly made with data series published by the International Monetary Fund (IMF, 2007) and the Bureau of Economic Analysis (BEA, 2008).

Figure 8a and b: Comparing real GDP at market prices and its growth in T21-USA to historical data



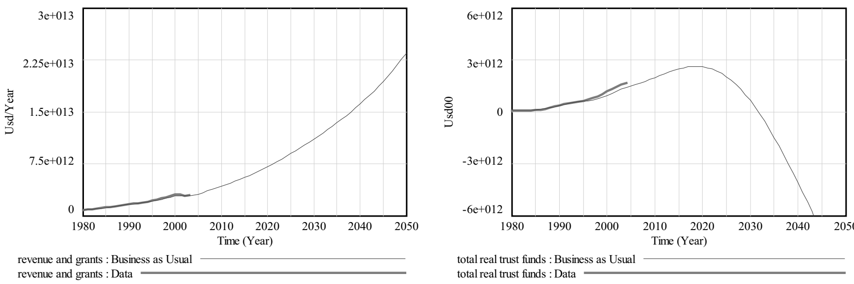
Government

Nominal federal government revenues and expenditure are projected to become respectively seven and eight times as high as their current value (3.37T and 4.40T USD in 2006). As a consequence, the overall fiscal balance (i.e. revenues minus expenditure) will remain negative throughout the simulation, and the continuing deficit will lead to a steady increase in public debt. By 2050, debt will be 2.25 times GDP, if left uncontrolled, compared to the current rate of about 0.6 times GDP. These figures include the Social Security Trust fund holdings of debt.

The behavior generated by the model is consistent with the assumptions underlying the business as usual scenario: government expenditures and revenues follow economic growth, the rising level of debt will increase annual interest payments, and trust funds start declining before 2025 and become negative after 2030. As a result, the accumulation of debt will be increasing as GDP grows and no restrictions and corrective measures are applied.

Although the behavior of the trust funds is consistent with the long-term scenarios generated by the Congressional Budget Office (CBO, 2006) and by the USA Social Security Administration (SSA, 2006), more work is needed to reach improved understanding of the dynamics of social security and medicare separately. For this reason, policies on contribution and expenditure, as well as on retirement age, are embedded in T21-USA and can be tested by the users with a dedicated interface.

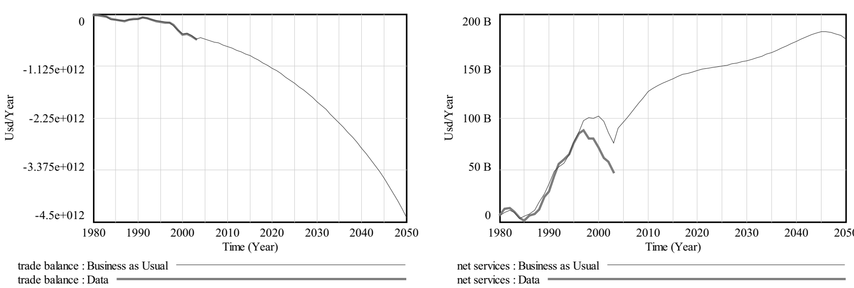
Figure 9a and b: Comparing government revenues and real trust funds in T21-USA to historical data



Rest of the World (ROW)

The Balance of Payments deficit is projected to grow slowly in the medium and long term. The negative performance of the current account (calculated as the sum of resources balance, net factor income and net transfers) is slightly offset by the growth in the capital and financial account as foreign investment in USA government bonds and other private sector assets will continue the current positive trends. However, this means that the foreign level of USA assets will increase.

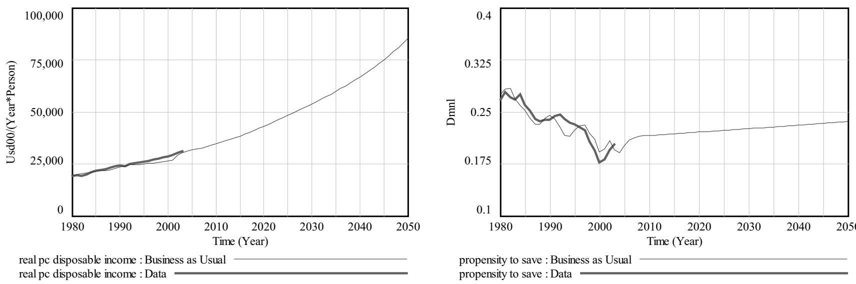
Figure 10a and b: Comparing trade balance and net services in T21-USA to historical data



Households

Real per capita disposable income is projected to rise over time due to the growth of GDP, conservative fiscal assumptions, and contained population increase. Per capita real disposable income reaches 85,000 USD, 2.65 times as high as in 2006. The propensity to save (and consume) in T21-USA is calculated as a function of income and interest rates. The latter are projected to be constant in the future, while income is increasing; this explains the growth in saving observed in Figure 11b, which recovers somewhat from the decline in the past two decades.

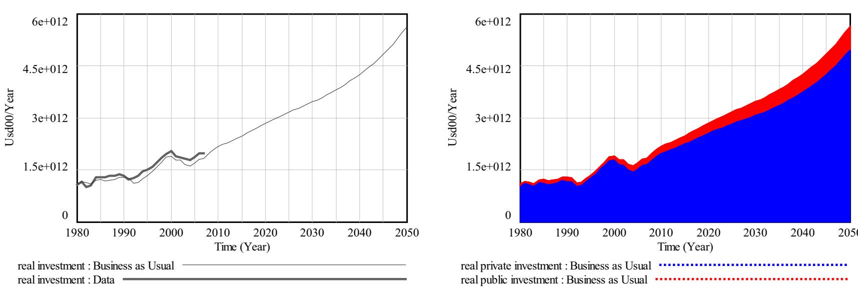
Figure 11a and b: Comparing real per capita disposable income and propensity to save in T21-USA to historical data



Real private and public investment (i.e. government infrastructure expenditure) both increase during the period 2006 – 2050 by three and four times, respectively. The share of private over total investment declines from 90.5% in 2006 to 88% in 2050.

The allocation of investment between services, industry and agriculture follow GDP growth in these sectors.

Figure 12a and b: Comparing real total investment and its composition in T21-USA to historical data



Behavior of the Environmental and Energy spheres

The results of the simulation of the Environment and Energy spheres are merged due to their numerous interconnections. Fossil fuel emissions derive from the consumption of oil, natural gas, and coal. Climate change is also a consequence of the accumulation of GHG emissions and therefore energy consumption. Land utilization for biofuels production and water availability for agriculture production and energy generation will be incorporated in the next phase of the T21-USA project. The behavior of the energy sectors will be presented first, emissions and climate change will follow.

The energy modules in T21 are built on the physical structure of the energy sector. They endogenously represent the dynamics of energy demand and production, take account of resource depletion among other sectors, and are included in the Environmental Sphere of the model. An endogenous representation of the energy sector and the utilization of a limited number of exogenous inputs are necessary to analyze and represent the energy transition. It has to be noted that the model tends to reproduce medium to longer-term trends, without taking into consideration short-term oscillations (e.g. monthly or even annual fluctuations in oil and fossil fuels prices).

The main outputs of the Energy Sectors included in T21-USA can be divided into national and international indicators. Demand, production, prices, and costs of different energy sources, together with the generation of emissions are calculated for both USA and the rest of the world (ROW). Energy demand by sector (residential, commercial, industrial and transportation); investment, expenditure; carbon cycle and contribution to climate change are represented only for the USA[8].

Energy demand, supply, prices and emissions are calculated as follows:

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[8] Historical data for comparison are taken from taken from Energy Information Administration (EIA), International Energy Agency (IEA), Organization of Petroleum Exporting Countries (OPEC), American

- Energy demand is influenced by GDP, energy prices, and technology;
- Supply is determined by demand, capital, technology, and availability of resources;
- Investments are determined by the profitability of the market and availability of resources;
- Prices are defined by the medium and long term demand-supply balance, as well as by the availability of resources and reserves;
- Emissions are generated by the amount and type of fossil fuel consumption.

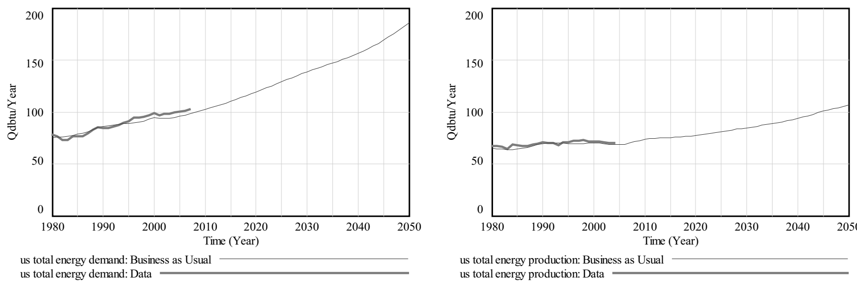
USA Energy Demand and Supply

Total energy demand, driven by economic growth, is projected to increase over time, reaching 186 Quadrillion BTU in 2050 (about 93% higher than its present value). The above-mentioned growth results from the combined effect of GDP (+300%), technology (+48%) and rising energy prices (+75%). While GDP has a positive impact on energy demand, both technology and price increases tend to reduce demand. As a consequence, the energy intensity of GDP is decreasing, although the total and per capita demand and consumption are increasing.

Domestic energy production is also rising over time, but cannot match the faster growth of demand. Total USA energy production reaches 107 QDBTU in 2050, registering a 55% increase with respect to 2006. As a result, energy imports increase (+187%), as well as USA dependence from foreign energy up to 40% from 33.5 in 2006.

Association of Petroleum Geologists (AAPG), British Petroleum (BP), Intergovernmental Panel on Climate Change (IPCC).

Figure 13a and b: Comparing USA energy demand and production in T21-USA to historical data

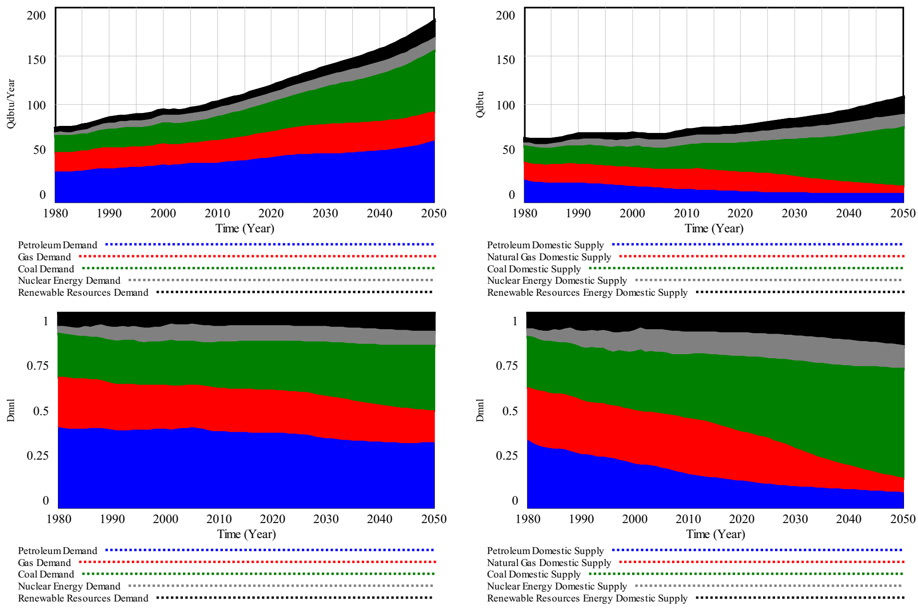


When looking at domestic energy demand and production by energy source in the business as usual scenario, coal becomes the dominant energy source for the USA economy. Indeed, the projected rise of oil and natural gas prices stimulates the substitution of coal and renewable energy sources for oil and gas. Moreover, energy sources that are not currently profitable may become profitable in the future (e.g. solar and wind energy generation, hydrogen, biofuels, etc.) due the increase in fossil fuel prices and cost abatement for renewable energy generation.

Despite an increase in total energy demand, the projected share of oil and natural gas in total energy consumption will decline from 40 to 33% and from 23 to 16%, respectively, by 2050. The share of coal consumption in the total is projected to increase from 22 to 33%, while renewable energy slightly grows (from 7 to 10%) and nuclear stabilizes at 7% (starting from 8% in 2005).

With regards to domestic energy production, the share of oil and natural gas will keep declining (from 20 and 28% in 2006 to 8% for each in 2050), coal's share will grow from 31 to 55%, while renewable and nuclear will raise from 9 and 12% to 12 and 17% respectively in 2050. The share of imports in total energy consumption will rise from 28 to 45% over this period to make up for the difference between demand and domestic production.

Figure 14a, b, c and d: Total energy demand and domestic production by energy source (14a and b), and energy sources share of demand and domestic production (14c and d) in T21-USA



Electricity Demand and Production

As shown above, total energy demand in the USA is projected to increase between 2006 and 2050. Such growth is determined, among other factors, by a growing demand for electricity (+163%, equivalent to 9.5 TWh/year), which in the USA is generated by using various energy sources. As shown below (Figure 15), the share of coal for electricity generation increases from 51% in 2006, to 62% in 2050; the natural gas share rises from 15 to 18%; while oil falls below 2%; nuclear declines from 21 to 12.5%; and renewable resources decrease from 10 to 5.5%. It is worth noting that these results are obtained by simulating the EIA reference case for renewable energy production (EIA, 2007). In order to allow users to test different assumptions about non fossil fuel electricity generation, wind, solar, geothermal, hydro, waste, and nuclear power generation are exogenous inputs to the model that the user can modify. As a consequence non fossil fuel electricity generation is not influenced by energy prices or by other feedback loops. When represented endogenously, renewable energy generation would increase over time as a consequence of rising fossil fuel prices, cost reduction, and efficiency improvement.

The decrease of oil and, relatively flat, gas shares are mainly explained by production peaks that occur and the resultant prices increases. Different factors explain the reduction of nuclear and renewable utilization for electricity production with respect to total electricity demand: in the business as usual scenario, production capacity is assumed to increase at a lower rate than electricity demand (EIA, 2007).

Figure 15: USA Energy demand in T21-USA

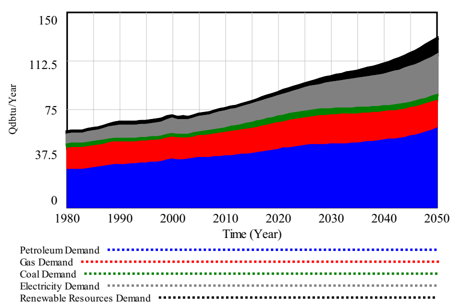
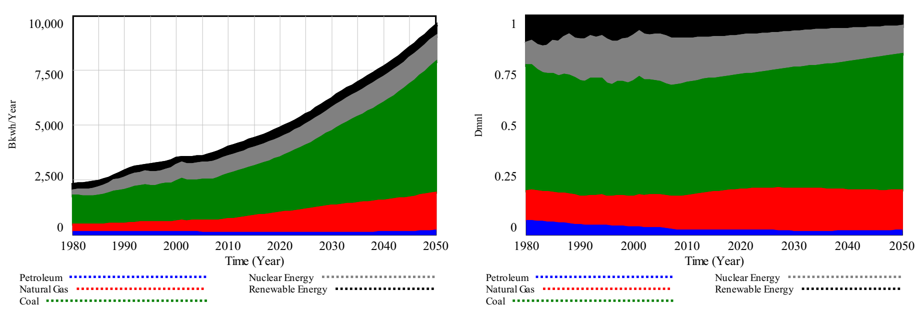


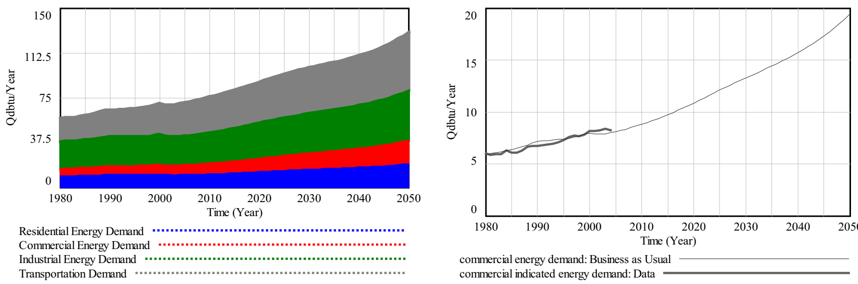
Figure 16a and b: USA Energy demand, electricity generation and shares for electricity production in T21-USA



Sector Energy Demand

Energy demand in the residential, commercial, industrial, and transportation sectors is projected to grow throughout the simulation period, following similar patterns. The only remarkable difference lies in a stronger effect of peak oil (e.g. fossil fuel price increase) in industry compared to the other sectors. The allocation of demand among the different sectors does not change significantly over time and remains as follows: commercial uses 12%, residential 15%, industrial 34%, and transportation 39%.

Figure 17a and b: Total energy demand by sector in T21-USA, comparing commercial energy demand in T21-USA to historical data



Transportation Energy Demand

Transportation accounts for about 40% of total energy demand in the US. Motor gasoline demand in T21 is calculated as total number of vehicles multiplied by the miles driven per vehicle per year and by the average fuel economy of the USA vehicle parc (CAFE). Total transportation fuel demand is presented below (Figure 18a). It is projected to increase from 27 to 48 QDBTU by 2050 and is composed of motor gasoline and substitutes such as biofuels, biodiesel, alcohol fuel, etc. (Figure 18b). Motor gasoline consumption is projected to rise to 207 Billion Gallons per year (from 157.5 in 2006) due to increasing miles driven and vehicle sales, which more than offset a modest improvement in fuel economy.

Figure 18a and b: Comparing transportation fuel demand and its composition in T21-USA to historical data

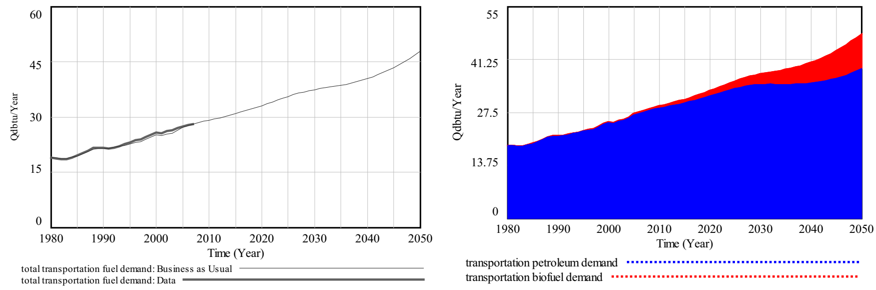
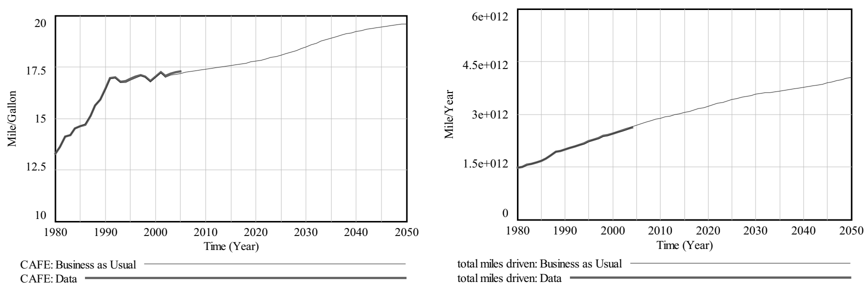


Figure 19a and b: Comparing average fuel economy and total miles driven in T21-USA to historical data



USA Petroleum Demand and Supply

The projection of national fuel demand indicates an increase of 58% by 2050, reaching 11.6 Billion barrels per year. The business as usual scenario forecasts 2026 as the turning point in oil demand due to substitution to other fuels. This is primarily the result of a sharp increase in the price of oil as the production peak is reached about then. Because of the transition phase, the dependency on foreign crude is projected to decrease after 2026, even if domestic production slows down to 1.5 Billion barrels per year by 2050. Crude oil demand slightly increases after 2045 due to the reduction of oil prices (as substitutes lower the demand for oil) and to the presence of infrastructure still running on oil (capital life in some sectors is longer than 20 years and substitutes for oil are assumed to be perfectly compatible with conventional engines).

Oil discovery and development are also shown. Both are sustained by high prices and technology improvement, but projections show a decline over the longer term due to the reduction of both undiscovered resource and discovered reserves.

Figure 20a and b: Comparing USA fossil fuels and oil dependency ratio in T21-USA to historical data

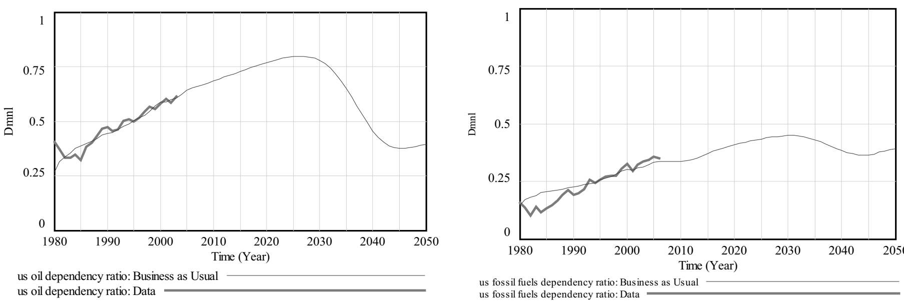
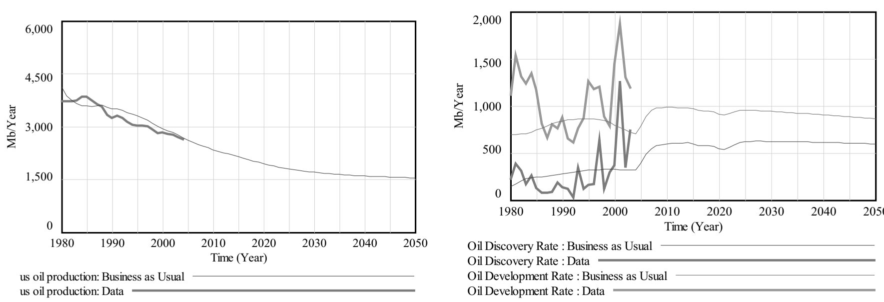


Figure 21a and b: Comparing USA oil production, discovery and development in T21-USA to historical data

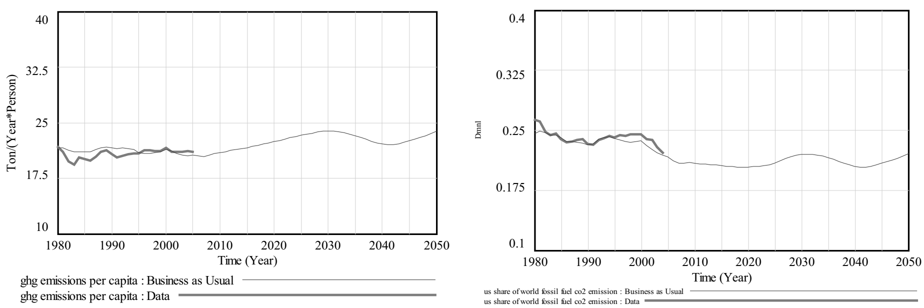


USA Fossil Fuel and GHG Emission

Highly influenced by energy consumption, USA fossil fuel emissions are projected to rise by 2050. The simulated mounting consumption of oil, gas, and coal generates 9.9 Billion Tons of GHG in 2050 (a 60% increase with respect to 2006). CO_2 emissions are projected to follow the same path (+61%), showing that effective and timely actions must be taken soon in order to reach the goals set by the Kyoto Protocol (UN, 1997) and help prevent a high and dangerous increase in global temperatures. Simulated GHG emissions intensity on GDP falls by 42.5% over the next 45 years, while per capita emissions go up by 16.5% reaching, 23.8 Tons per year per person.

The USA consumed about 21% of the total fossil fuels produced worldwide in 2006 and generated the same share of carbon emissions. The business as usual scenario projects the same relationship throughout 2050, which indicates that emissions in the USA and the rest of the world grow at the same rate.

Figure 22a and b: Comparing fossil fuel GHG emissions in tons, per capita, and contribution of USA to World emissions in T21-USA to historical data



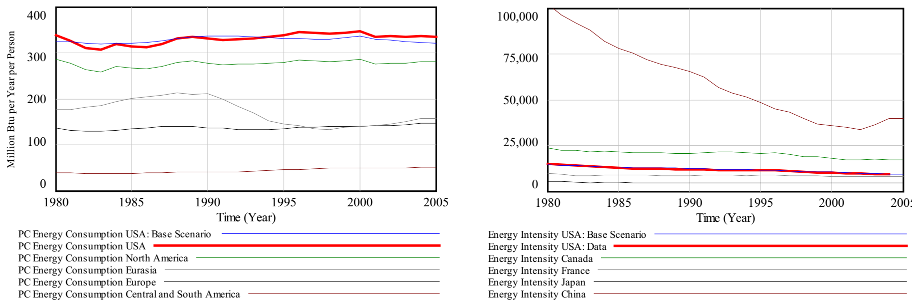
Rest of the World Energy Demand and Supply

Comparing per capita energy consumption and energy intensity between the USA and the rest of the world demonstrates that the American economy is not as efficient as many other industrialized countries. This suggests that there is a high margin for conservation and efficiency improvements in the USA, and that it is feasible.

Per capita energy consumption in the USA in 2006 is equal to 323 Million BTU per year per person (and it is projected to increase to 450 MBTU/person/year by 2050). The average is 280 MBTU/person/year in North America (including Canada and Mexico), 146 in Europe, and 70 for the world as a whole.

Energy intensity of GDP (i.e. energy consumption per unit of GDP) is lower in Germany, France, and Japan than the USA; however, it is higher in Canada and China (though the latter is quickly improving).

Figure 23a and b: Comparing USA per capita energy consumption and energy intensity of GDP in T21-USA to historical data and to foreign regions and countries



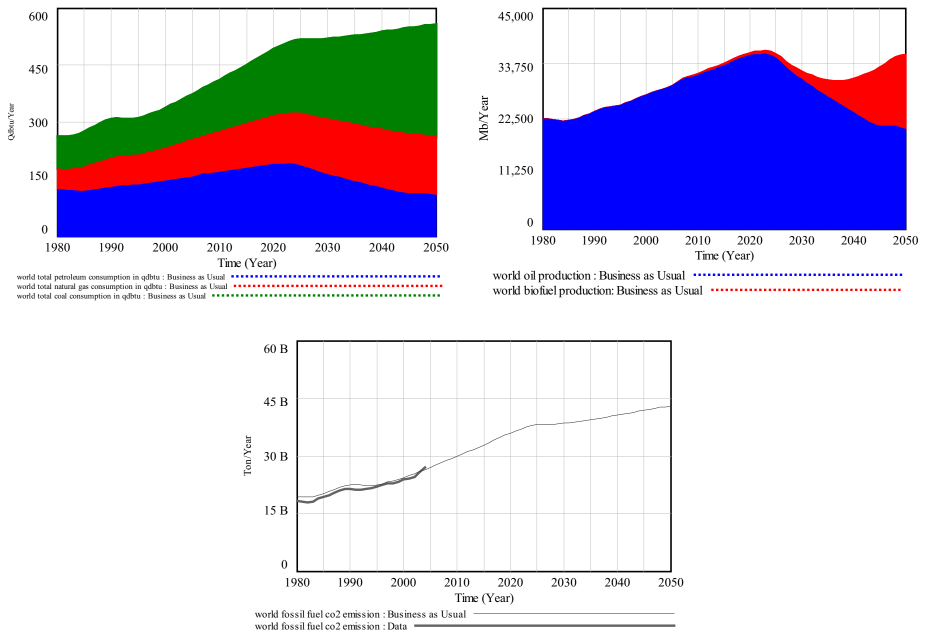
World fossil fuels demand is increasing towards 2050, reaching 556 QDBTU (+45.5% with respect to 2006). Figure 24b clearly shows the peak of oil production (in 2023) and an increasing demand of coal.

Projected world fuel demand for petroleum and its substitutes rises by 32% in 2050 compared to 2006, reaching 41,000 Million barrels (Mb) per year. However conventional oil production falls by 45%, having reached its peak of 35,650 Mb/year in 2023, and substitutes make up the difference. Various policy variables have been incorporated in T21-USA model to simulate different scenarios for world oil production. According to these simulations, the turning point of peak production could be achieved as early as a few years from now or as late as in 2040 at 45,000 Mb/year.

World natural gas production is projected to increase by 53% in 2050 compared to 2006, reaching its peak at 153,000 Billion cubic feet (Bcf) in 2044 (96,500 in 2006) and then declining to 147,500 Bcf/year. Coal production grows from 5,900 Million Short tons (Mst) in 2006 to 14,000 Mst in 2050, an increase of 138%. The demand for the generic substitutes for oil included in T21-USA is projected to represent 6% and 44% of world fuel demand in 2030 and 2050, respectively.

World fossil fuel CO_2 emissions are projected to increase by 55%, reaching 43 Billion tons per year in 2050.

Figure 24a, b and c: World fossil fuels and liquid fuels demand in T21-USA (24a and b); Comparing world fossil fuels carbon dioxide emissions in T21-USA to historical data (24c)

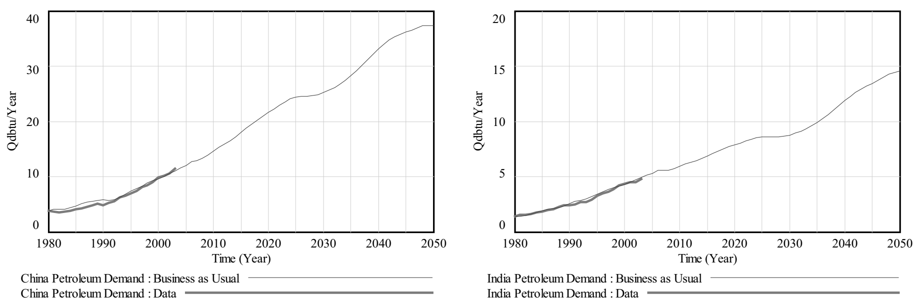


World fossil fuel demand is projected to increase at a lower rate than in the USA (45.5% relative to 52.8%), mainly due to lower dependency on coal for electricity production, lower per capita consumption, and lower capacity to absorb high energy prices.

In the case of fast growing countries such as China and India, simulated petroleum demand increases by 200% (7,000 Mb/year) and 165% (2,700 Mb/year), respectively, in 2050. Natural gas increases by 200% (4,500 Bcf/year) in China and by 320% (4,200 Bcf/year) in India. Coal demand grows by 214% (6,000 Mst/year) in China and by 188% (1,300 Mst/year) in India. It has to be noted that in the business as usual scenario the annual economic growth of China and India is projected to decrease linearly to 2% and 3% respectively by 2050.

The impact of growing demand from large developing countries on the availability of resources for the USA is visible. China and India's consumption will reduce the availability of fossil fuels (especially oil and gas) for the USA for two main reasons. First, China is taking care of future petroleum needs by buying oil companies and securing availability for the future. Also, the geographical location of China and India is an important asset: these countries are closer to the net exporting countries (e.g. Russia and the Middle East) than America. These factors will affect the prices faced by the USA, that is why it is assumed that all the oil domestically produced, even if more expensive and imported oil, is consumed.

Figure 25a and b: Comparing China and India petroleum demand in T21-USA to historical data



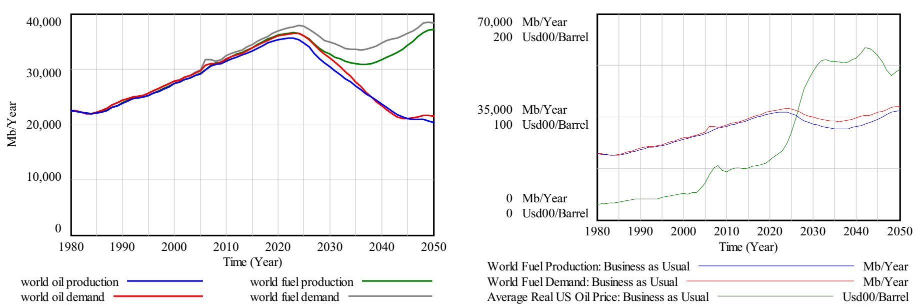
Oil Price

Historical data tell us that the price of oil decreased over the years until the price shocks of the mid 1970s and early 80's. At that time, petroleum price increased due to an apparent shortage of oil, which unveiled itself after the domestic production peaked in the USA. As soon as world production increased (especially the Saudi Arabian oil production), prices returned to their original level. Nevertheless, an important factor characterizing the energy market was revealed: the oil resource is finite and, as soon as production reaches its peak, petroleum prices will increase. The rise of oil prices can be immediate and steep if capacity to produce substitute fuels is not in place to support a smooth and gradual transition, or if the production of alternative sources can cope with demand (see Figure 26b).

ROW and USA total fuel demand and supply are presented in Figure 26a and b to explore the transition beyond conventional oil and the dynamics of oil price. The graph on the left shows that increasing fuel demand cannot be satisfied by conventional oil production starting from 2020. When petroleum prices increase (i.e. when production is not able to cope with demand, see Figure 26b), demand for oil substitutes starts growing (Figure 24a). Since it takes time to create production capacity, a demand supply gap takes place, sustaining high prices. Continuously growing demand for fuels makes it more difficult for the production gap to be closed, since it takes time for the additional capacity to be completed and the increasing demand contributes to maintaining the gap over a longer time period. When production capacity of substitutes is finally able to close the gap, oil prices decrease.

The International Energy Agency (IEA) has recently confirmed the above. In fact, IEA foresees the creation of a prolonged mismatch between oil demand and supply (IEA, 2007) as shown in Figure 26a and 26b over the next 10 to 15 years.

Figure 26a and b: USA and world fuel demand and supply in T21



Real world and USA oil prices are projected to increase 2.5 and 2.8 times by 2050 with respect to 2006. This is due to the decreasing availability of resources and reserves, growing demand, and a delayed process of producing substitutes from renewable resources. Nevertheless, the graphs below (see Figure 27a and b) show that once the gap between demand and supply is reduced and substitution takes place, the price of conventional oil decreases from its peak. However, the long-term price trend is still increasing due to increased production costs: the smaller the amount of conventional oil available (in form of resource and reserves), and the higher the cost to recover it (both in terms of economic investment –technology- and of energy return on investment –EROI-).

The oil price in the USA is higher than in the rest of the world after the transition due to its increasing depletion of oil and growing fuel demand. The delayed transition process is assumed to have a stronger effect on a nation highly dependent on oil.

Figure 27a and b: Comparing average real USA and world oil price in T21-USA to historical data

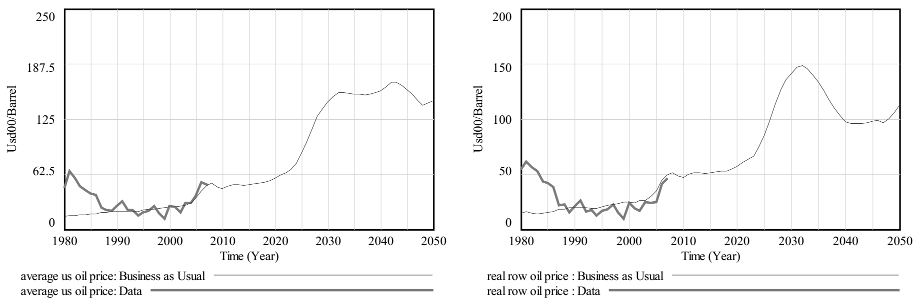
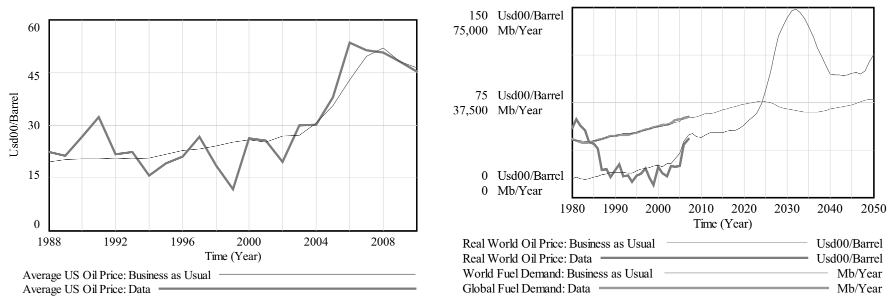


Figure 28a shows the historical behavior of oil price (1986 to 2009, EIA data compared to the T21 USA projection). Speculation and short-term shocks are not taken into consideration by T21. Therefore the simulated price tends to reproduce the medium term trend of price, not short-term fluctuations. As for the future, energy prices have a negative effect on energy demand. The case of world oil price and global fuel demand is shown in Figure 28b.

Figure 28a and b: Comparing real petroleum price in T21-USA to historical data (28a) and world fuel demand (28b)



Sensitivity Analysis

The following sensitivity analysis shows the ranges of possible results obtained by simulating different assumptions on oil resource and reserves availability. A *random uniform* distribution has been used for the simulation of 500 scenarios (i.e. Monte Carlo Simulation) where resources and reserves are subject to a change between -500 and +500 billion barrels in 2010. Once resources are added to their stock, it is assumed that it takes 10 years or more to discover them. When reserves are added it is assumed that it takes at least 6 years to develop and recover them. Not all resource and reserves added can be discovered or produced; that amount is defined by the fraction discoverable and recoverable, which is endogenously calculated by the model.

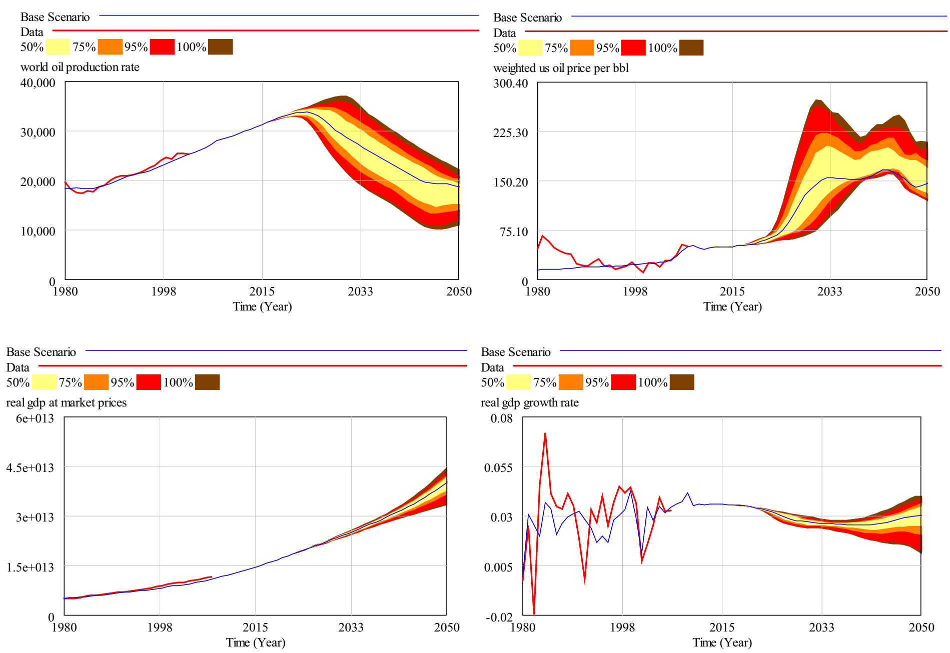
The two extreme scenarios assume that total oil originally in place is equal to 3.9T and 5.9T barrels (4.9T in the business as usual scenario). The ultimate oil recovery in 2050 ranges between 2.5T (56% of the total oil in place) and 3.3T (78.0%); in the business as usual scenario (BAU) the total amount recovered and recoverable in 2050 is equal to 2.9T (59.2%), in line with the published estimates of world oil ultimate recovery (USGS 2000).

These simulations show that reducing or increasing the amount of resources and reserves available influence oil production, oil prices, and GDP. Reducing resources and reserves generate an earlier peak and a faster production decline.

These two effects make oil prices increase faster, but also decline earlier (because substitution will take place earlier). In addition, since energy prices are negatively correlated to total factor productivity, GDP growth declines during the energy transition, to increase again once substitution in place and the oil price falls.

Interestingly, the oil price (Figure 29b) reaches a double maximum. This is due to the transition beyond oil for the first peak, and to the utilization of expensive domestically produced petroleum in the second case. It is assumed that since world oil production decline generates a mismatch between demand and supply, all the petroleum produced domestically, even if more expensive that the one imported, will be consumed.

Figure 29a, b, c and d: Results of the sensitivity analysis for world oil production, average USA oil price, real GDP and its growth rate



It has to be noted that these simulations are run in relation to the base scenario, where energy production from renewable energy grows slowly and where the economic outlook (based on a continuation of expenditure patterns) does not look very positive. In addition, renewable energy production is limited by a 5-year delay that slows down production capacity. Also, 2006 is considered to be the first year in which demand and investment in biofuels take place. As a consequence, under these conditions, a high gap between demand and supply can have a strong impact on the economy. For these reasons, users are allowed to change, among others, the elasticity of GDP to price, the delay time coupled with biofuels production, and the amount of resource and reserves available.

Behavior comparison

The results of the analysis carried out with customized T21 and MCM models shows that the projections created may differ from the ones published by the Energy Information Administration (EIA) or the International Energy Agency (IEA). The dynamic models utilized for this research are able to highlight the presence of elements of policy resistance and the manifestation of side effects driven by the causal feedback loops underlying the structure of the system analyzed.

Despite difficulties in comparing projections due to the wide boundaries and extended time horizon characterizing models used to carry out the present research work, the EIA and the IEA longer term outlooks can be used to start highlighting similarities and differences among these studies, at least concerning selected macro variables such energy demand and supply.

This brief analysis focuses on population (social sphere), GDP growth (economic sphere), international oil prices, energy demand and supply (energy sphere), and carbon emissions (environmental sphere).

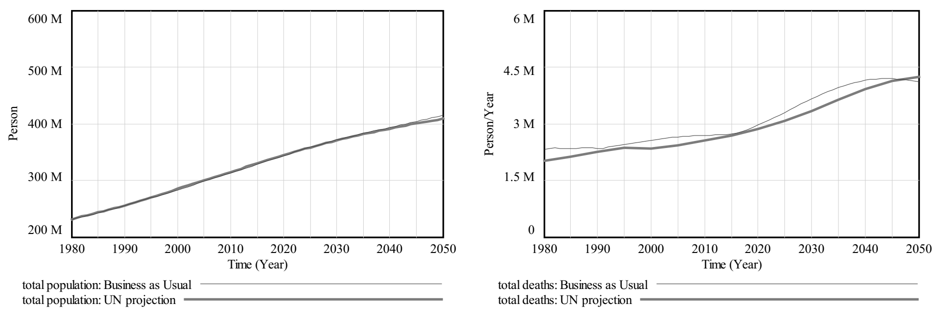
Social Sphere: Population

Projections of the Social Sphere for the United States are in line with the data series published by the United Nations Population Division (UN, 2007) and the

Energy Information Administration (EIA, 2007). Total population, deaths, life expectancy, and labor supply are presented below.

Total population in the United States is projected to grow by 38% in the period 2006 – 2050 with T21, reaching 414.5 million people. The UN World Population Prospects projects 408.6 million in the medium case (469 millions in the high growth case).

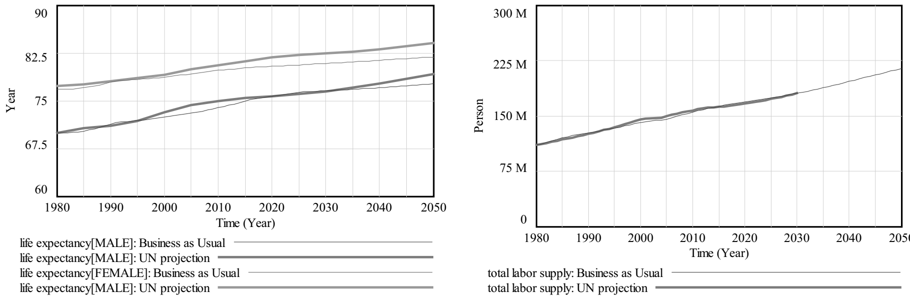
Figure 30a and b: Comparing total population, births and deaths in T21-USA to U.N. projections



Life expectancy is projected to grow from 79.5 years in 2006 to 82 in 2050 for females, and from 73.5 years in 2005 to 77.5 in 2050 for males, in average one year below UN's projections.

Labor supply and employment are both projected to increase, in line with the positive trend observed since 1980. Simulated labor supply increases by 45% (reaching 213.5 million, matching EIA's projections) during the period 2006 – 2050, with employment rising by 43.5% to 198 million (against 186 million projected by EIA).

Figure 31a and b: Comparing life expectancy and labor supply in T21-USA to UN (31a) and EIA (31b) projections



Economic Sphere: GDP

T21-USA projections of the Economic Sphere are in line with the data series published by the Congressional Budget Office (CBO) and by the Energy Information Administration (EIA). Real GDP and its growth rate are compared with EIA (EIA, 2007) and CBO (CBO, 2006) projections respectively.

In the baseline scenario simulated with T21-USA (business as usual case) real GDP at market price is projected to become four times as high in 2050 as in 2006, reaching 40 trillion USD (using 2000 as the constant dollar base year). Among sectors, agriculture is projected to grow by 86%, industry by 128%, and services by 325%. The share of each sector in GDP is as follows: agriculture, which accounted for 1.5% in 2006, is projected to decrease to 0.75% by 2050; industry's share declines from 24% to 14.25%; and services' portion increases from 74.5% to 85%. In the economic sectors of T21-USA, historical comparison is mainly made with data series published by EIA, the International Monetary Fund (IMF, 2007) and the Bureau of Economic Analysis (BEA, 2008). EIA's outlook, reaching 2030, is chosen for comparison as it is identical to CBO's (which is extended to 2016 only) and provides a longer time frame for comparison. T21-USA projects GDP at $23.6 trillion against EIA's $23.1 trillion and is below the value indicated in the AEO 2006. The same will be observed for energy indicators, that may be higher than EIA's 2007 projections, but are lower than the 2006 outlook. Projected GDP growth rate with T21 equals 3.3%, higher than the 3% projected by

EIA. It has to be considered that the tax cut applied by President G. W. Bush was lowered when simulating the baseline scenarios of T21 USA over the longer term, to avoid the creation of an economic recession after 2040. This modification is responsible for the projection of a slightly higher GDP growth rate between 2006 and 2030.

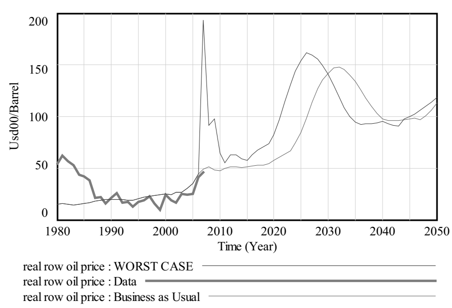
Figure 32a and b: Comparing real GDP, and its growth rate in T21-USA to EIA (32a), CBO (32b) projections

Worst case scenario: oil production, prices and GDP

Towards the end of 2006 a new set of assumptions were simulated with T21-USA. These were grouped in the "Worst Case" scenario, which simulates a sudden reduction of 15% of available world identified and recoverable reserves, equal to 300 billion barrels, in 2008. This could result from a political crisis in the Middle East that cut oil production and exports for a variety of reasons. Such a change would generate an immediate jump of oil price to about \$200/barrel due to an unexpected shortage and consequent short-term production decline, similar to the concerns raised in late 2007 and early 2008 by the IEA. The increase in oil price would then stimulate fossil fuel exploration and recovery; nevertheless world oil production will enter a plateau phase and peak between 2015 and 2020. As a consequence the energy transition will take place before 2030 as the oil price indicates (see Figure 33). Biofuels production would increase faster than in other scenarios, but due to capacity construction delays and low net energy contribution will not be able to satisfy liquid fuels demand.

The supply shock has a negative short-term impact on the economy. Under these assumptions GDP growth would fall by 1.4% in 2008 and 2009 with respect to the business as usual scenario. Due to higher projected energy prices between 2008 and 2030, the economy will suffer also over the longer term. In the short term, the effects of high energy prices can be absorbed by high revenues from other sectors and by low unemployment, but over the longer term the damages could become irreversible. In this regard, the model shows that an economic recession takes place after 2030 due both to the high costs of the energy transition and to the energy shortage of 2008-2010. This scenario assumes that no investments are allocated to renewable energy, government revenues and expenditures remained unchanged, trust funds turn negative in 2035 and government debt (uncontrolled) is 4.5 times GDP in 2050.

Figure 33: Comparing real world oil price in the WORST CASE and business as usual scenarios



Energy Sphere: Demand and Consumption

Oil Prices

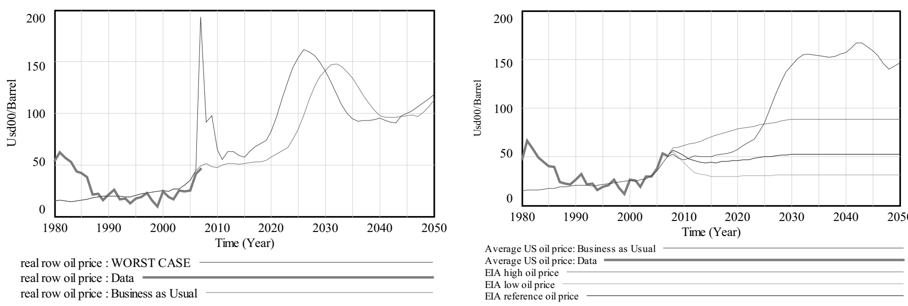
Real world and USA oil prices are projected to increase 2.5 and 2.8 times by 2050 with respect to 2006 in the United States model, where the energy transition is projected to take place shortly after 2030. This is due to the decreasing availability of resources and reserves, growing demand, and a delayed process of producing substitutes from renewable resources. Nevertheless, once the gap between demand and supply is reduced and substitution takes place, the price of conventional oil decreases from its peak. However, the long-term price trend is still increasing due to increased production costs: the smaller the amount of conventional oil available (in form of resource and reserves), and the higher the cost to recover it (both in terms of economic investment –technology- and of energy return on investment –EROI-). Oil price in the United States is projected to be higher than in the rest of the world after the energy transition due to its higher and increasing oil depletion and growing fuel demand.

Oil price in the North America model grows starting from 2011, when world oil production is assumed to decrease. Projections from the United States models are here considered for comparison with the EIA projections as the baseline scenario is set up with similar assumptions.

World oil prices are difficult to compare across models because they highly depend on the assumptions used for the availability of oil resource and reserve, demand and speculation/market volatility. T21 and MCM, as well as NEMS, focus on the longer term and do not aim at projecting short term price fluctuations. Nevertheless, energy prices in T21 are dynamically calculated by the interaction of various feedback loops that generate non linear behavior instead of linear projections.
Two scenarios are shown below, the baseline and "Worst Case" both simulated with T21-USA simply by varying the amount of reserves available. In both cases T21 shows slightly increasing prices until global oil production peak is reached, whenever that happens, due to increasing depletion and growing demand. Following the decline or a plateau in world oil production, drivers of the energy transition (including the availability of substitutes for oil, the flexibility of energy supply and the contribution of renewable energy, GDP growth and energy demand), will determine the value of oil price. The effect of the energy transition on oil prices is very visible in T21-USA and North America, while it is not treated with NEMS and WEM. NEMS in particular, projects three scenarios, a high,

medium and low energy price outlook, as shown below. In the reference case of the latest AEO, world oil prices decline from current levels through 2016 and then gradually rise to about $80 in real terms (2000 dollars). This pattern of falling and then rising oil prices is seen in many long-term projections. Projections from T21 seem to be the only ones proposing a growing longer term trend for oil prices under all conditions examined.

Figure 34a, b: Comparing energy intensity of GDP and oil price in T21-USA to EIA projections

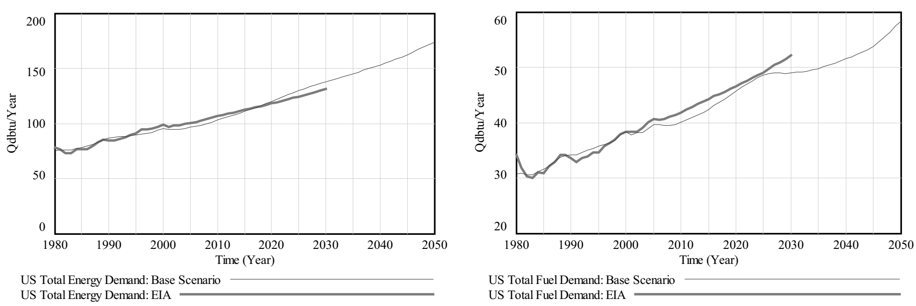


What is most interesting about projections of oil prices is not the absolute value projected, instead it is the mechanism underlying their calculation. In other words, the equations that allow for the dynamic calculation of energy prices are the value added of the present research work concerning energy prices. The EIA states that: *"Recent volatility in crude oil prices demonstrates the uncertainty inherent in the projections."* (EIA, 2008). This implies that NEMS as well as Global Insights, Inc. (GII, 2007), Deutsche Bank (DB) and IEA models, based on econometric or economic laws, are not able to identify the underlying forces determining oil prices and are heavily dependent on historical data (which actually determine the value of future projections). As a matter of fact, both GII and DB define the range of crude oil price projections for 2030, from as low as $52 per barrel (GII) to a high of $90 per barrel (DB) (EIA, 2008). The baseline scenario of T21-USA, with peak oil taking place shortly after 2030, projects oil prices to be slightly below $150 per barrel. This value changes automatically depending on the structural and numerical assumptions used (such as oil reserves), without directly relying on history to make future projections.

Total Energy Demand

Total energy demand, driven by economic growth, is projected to increase over time, reaching 186 Quadrillion BTU in 2050 (about 93% higher than its present value). The above-mentioned growth results from the combined positive effect of GDP (+300%), and the negative impact of technology (+48%) and rising energy prices (+75%). The EIA projects total energy demand to equal 131.2 quads by 2030, against 138.7 quads indicated by the BAU scenario of T21-USA (+5.75%). This discrepancy is driven by the fact that projected GDP with T21 is 5.26% higher than EIA's in 2030. The average absolute percent difference from 1980 until 2030 in the EIA (data and projections) and T21-USA projections is 2.74%.

Figure 35a, b: Comparing total energy and fuel demand in T21-USA to EIA projections



Despite an increase in total energy demand, according to T21-USA, the projected share of oil and natural gas in total energy consumption will decline from 40 to 33% and from 23 to 16%, respectively, by 2050. The share of coal consumption in the total is projected to increase from 22 to 33%, while renewable energy slightly grows (from 7 to 10%) and nuclear stabilizes at 7% (starting from 8% in 2005). The EIA projects very similar values for the energy supply mix. Similarly to what projected by EIA, liquid fuels demand increases despite the improvement of fuel efficiency standards, due to increasing population and income. Increasing consumption is projected for the transportation sector, both air and road.

Total Energy Supply

With regards to domestic energy supply, the share of oil and natural gas is projected to decline (from 20 and 28% in 2006 to 8% for each in 2050), coal's share grows from 31 to 55%, while renewable and nuclear raise from 9 and 12% to 12 and 17% respectively in 2050. The share of imports in total energy consumption is projected to rise from 28 to 45% over this period to make up for the difference between demand and domestic production.

In 2030 EIA's projections indicate a 40% penetration of oil, 20% for natural gas, 26% for coal, 7% for nuclear energy and 6% for renewables. T21 projections, accounting for the energy transition triggered by the decline in world conventional oil production shows, with respect to the EIA, already in 2030, smaller shares for oil (10%), similar values for natural gas, that still has to peak (19%), and higher values for the substitutes for oil: coal (45%), nuclear energy (12%) and renewables (12%), which become relatively cheaper in a business as usual, market driven scenario.

Electricity sales and generation

The projections for total electricity sales in 2030 are about the same (5,478 billion kwh against 5,695) in the AEO2007 reference case and T21-USA. The annual rate of demand growth in both projections is about 1.5 percent per year from 2005 to 2030.

The AEO2007 reference case shows constant real electricity prices throughout the simulation while T21 projects increasing costs starting from about 2015 and doubling electricity price by 2030. This is mainly due to the impact of peak oil on the energy market, including increasing demand for coal, which becomes more expensive.

Electricity generation from fossil fuel and renewable resources again shows similarities between T21 and EIA projections. The long term trend generated by T21, accounting for the energy transition beyond oil, indicates that the share of coal for electricity generation increases from 51% in 2006, to 62% in 2050; the natural gas share rises from 15 to 18%; while oil falls below 2%; nuclear declines from 21 to 12.5%; and renewable resources decrease from 10 to 5.5%. It is worth noting that these results are obtained by simulating the EIA reference case for renewable energy and nuclear electricity generation (EIA, 2007). The EIA projects liquid fuels to account for 2% of electricity generation in 2030, natural gas 12%, coal 59%, nuclear power 18% and renewable energy 10%. The BAU scenario of T21-USA indicates a 1.45% penetration for liquid fuels, 19% for natural gas, 55% for coal, 16.5% for nuclear power, and finally 7.5% for renewable energy. The main difference between the two sets of projections consists in the fact that T21 projects higher natural demand and supply until 2030, therefore natural gas penetration is higher and coal use is lower in T21 projections.

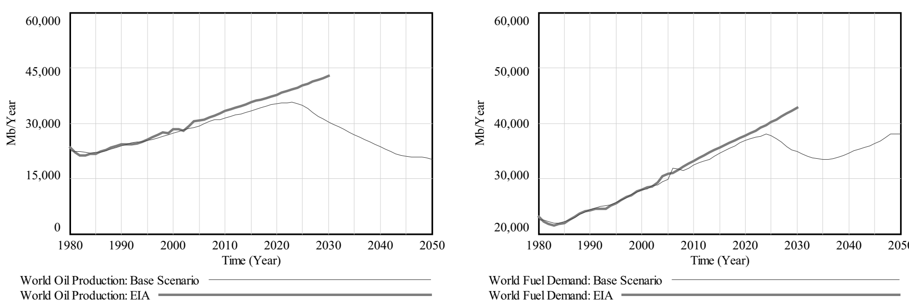
Energy Sphere: World Indicators

T21-USA projections indicate that world liquid fuel demand will rise by 32% in 2050 compared to 2006, reaching 41,000 Million barrels (Mb) per year. However conventional oil production falls by 45%, having reached its peak of 35,650 Mb/year in 2023, and substitutes make up the difference.

Various policy variables have been incorporated in T21-USA model to simulate different scenarios for world oil production. According to these simulations, the turning point in conventional oil production could be reached as early as a few years from now or as late as in 2040 at 45,000 Mb/year.

The EIA projects conventional oil demand to reach 38,835 Mb per year in 2030 and total liquid fuel supply to grow to 42,800 Mb, with the difference being supplied by unconventional oil and other liquid fuels (3,991 Mb/year). T21-USA projects conventional oil supply reaching a plateau phase after 2020 at about 35,500 Mb to decline to 30,500 Mb by 2030. During the same years world oil demand is projected to reach a maximum value of 36,500 Mb per year to decline, due to increasing oil prices, to 32,000 Mb per year in 2030. In such simulation, investments in production capacity for oil substitutes are assumed to take place five years before global production declines. The time lag existing to build capacity and bring production on stream makes so that consumption of liquid fuels will decline and oil prices will remain high until the energy transition is completed.

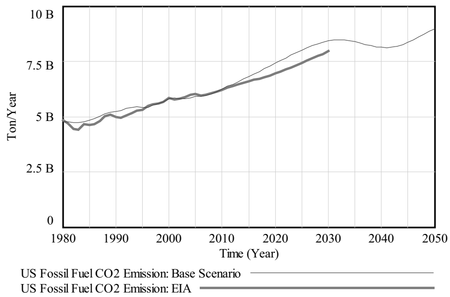
Figure 36a and b: Comparing world oil production and fuel demand in T21-USA to EIA projections



Environmental Sphere: Emissions

Carbon dioxide emissions reflect fossil fuel consumption and are projected to be slightly higher in 2030 by T21-USA with respect to EIA's projections (8.4 against 7.95 billion metric tons, a 6.5 difference). It is worth noting though, that due to the decline in global oil production and the subsequent energy transition, CO2 emissions are projected to arrest their growth after 2030.

Figure 37: Comparing USA carbon dioxide emissions in T21-USA to EIA projections



C

Appendix C: Models Documentation

Introduction

The structural characteristics of energy sectors in different geographical contexts present similarities. The same drivers form many of the core feedback loops defining the behavior of energy system, though their strength and impacts vary according to the social, economic and environmental context. As a consequence, some of the tools built to carry out the preset research work use similar building blocks. This documentation analyzes them and presents the main by sectors of the energy sphere.

The underlying structure of the *Energy Demand* sector is introduced first. This covers the modules used in the North America (NA) and United States (USA) models, for residential, commercial, industrial and transportation demand. The specific modules developed for the Energy Intensive Manufacturing sectors and Electrified Rail studies are presented next. Finally, demand from the rest of the world (ROW), with emphasis on China and India (NA/US model) and Canada and Mexico (NA model) and Ecuador end the presentation of the *Energy Demand* sector.

Energy Supply is documented for fossil fuels (USA, Canada, Mexico and ROW) as well as for tar sands (Canada) and ethanol (USA). While the U.S. and ROW fossil fuel supply sectors are largely endogenous and use a limited number of exogenous variables, the Canada and Mexico models are simplified and build on the results of existing studies, which are used as assumptions. Ethanol production is presented for the U.S., and electricity generation is documented for the Ecuador, NA and USA models. EROI calculations are documented for U.S. fossil fuel production.

Total demand, supply, and fossil fuels trade are calculated and presented for the U.S., Canada and Mexico. The main output of these modules is the demand supply balance, which is used to calculate energy prices and production costs. These are calculated for fossil fuels, for the U.S. and ROW. Energy investment, capital and technology are presented for fossil fuels and renewable resources, for the U.S. energy sector.

Emissions (CO_2, CH_4, N_2O, SO_X) are calculated for U.S., Canada, Mexico and ROW. Greenhouse gas emissions (GHG) are presented and calculated only for the U.S. and ROW. These sector converts energy consumption into emissions and borrow from research carried out by the Millennium Institute (Millennium Institute, 2005) and materials form the IPCC (IPCC, 1996).

The table below illustrates the main sectors and building blocks used to customize the North America, USA, Ecuador models as well as the modules created to carry out the transportation and energy intensive analyses. The table includes sectors, correspondent modules belonging to different models and the country upon which the models were customized.

Table 4: Energy sectors presented in the documentation: corresponding modules, models and countries customized.

Sector	*Correspondent Modules*	*Model*	*Country*[9]
Energy Demand	Residential, commercial, industrial, transportation	US	US
	Energy intensive industries	IIM-CP[10]	US, ROW
	Electrified rail	US	US
	Canada and Mexico China and India Ecuador ROW	NA US, NA EC US, NA	CA, MX CN, IN EC ROW
Energy Supply	Conventional oil production Conventional oil exploration Conventional oil development Conventional oil technology	US, NA	US
	Fossil fuel production: oil, natural gas, coal	US, NA	US, CA, MX, ROW
	Tar sands	NA	CA
	Ethanol	NA	US
	Electricity	US, NA, EC	US, CA, MX, EC
	EROI	NA	US
Total Demand, Supply, and Trade	Fossil fuels (oil, natural gas, coal)	US, NA, EC	US, CA, MX, EC, ROW
Energy Price and Cost	Fossil fuel (oil, natural gas, coal)	US and NA	US, ROW
Energy Sources Investment, Capital and Technology	Fossil fuel (oil, natural gas, coal), renewable resources	US, NA, EC	US, ROW
Fossil Fuel and GHG Emissions	US, Canada, Mexico and ROW	US, NA, EC	US, CA, MX, EC, ROW

9 US, United States; ROW, rest of the world; CA, Canada; MX, Mexico; CN, China; IN, India; EC, Ecuador.

10 Integrated Industry Model - Carbon Policy (IIM-CP)

Energy Demand

Sector Energy Demand

Purpose and Approach

The purpose of the Energy Demand modules is to calculate and represent energy demand in the residential, commercial, industrial, and transportation sectors. Sectoral energy demand is disaggregated into five energy sources (oil, natural gas, coal, renewable energy and electricity), following the EIA classification contained in the Annual Energy Review (EIA, 2007).

Sectoral energy demand is calculated for the US and is contained in the North America and US models.

Explanation

Major Assumptions

- Five energy sources are considered (oil, natural gas, coal, renewable energy and electricity);
- Energy demand is influenced by GDP, energy prices (energy demand of a specific source is influenced by its price) and technology;
- Relative price of one energy source with respect to the other sources only generates shifts from one source to the others, not a reduction in consumption.

Given the similarity of the residential, commercial and industrial energy demand structure, the residential module will be used to show the characteristics of the Sectoral Energy Demand sector. Differences between those three modules and the transportation energy demand are illustrated.

Input Variables

Variable Name	**Module of Origin**
Coal Multiplier for Shock Price	Effect of Price on Demand
Coal Price Substitutability	Energy Prices
Electricity Price Substitutability	Energy Prices
Natural Gas Multiplier for Shock Price	Effect of Price on Demand
Natural Gas Price Substitutability	Energy Prices
Oil Multiplier for Shock Price	Effect of Price on Demand
Oil Price Substitutability	Energy Prices
Real GDP at Market Prices	Investment
Relative Resources Technology	Technology
Renewable Energy Multiplier for Shock Price	Effect of Price on Demand
Renewable Resources Price Substitutability	Energy Prices

Output Variables

Variable Name	Module of Destination		
	Same Sector	Other Energy Sectors	Other Sectors
Normalized Residential Renewable Resources Demand		Demand and Import: Renewable Resources	
Normalized Residential Coal Demand		Demand and Import: Coal	
Normalized Residential Oil Demand		Demand and Import: Oil	
Normalized Residential Electricity Demand		Demand and Import: Electricity	
Normalized Residential Natural Gas Demand		Demand and Import: Natural Gas	

Constants and Table functions

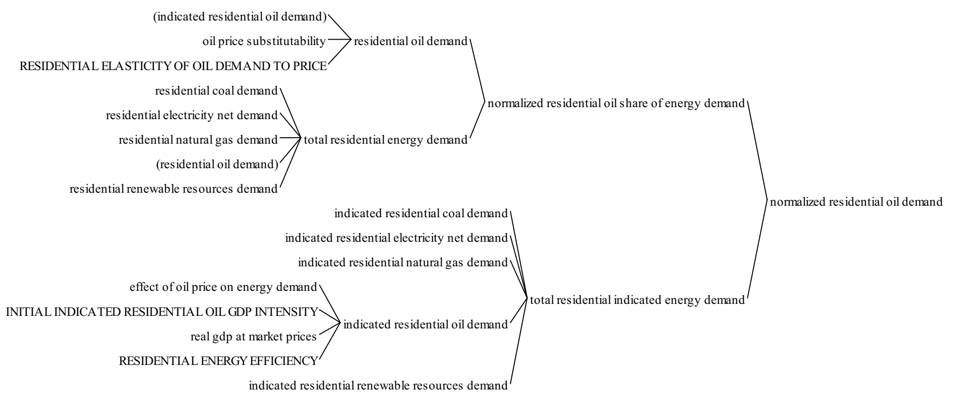
Variable Name	Type of Variable	Source for Estimation
Initial Intensity of Coal in Residential Energy Production	Constant	EIA
Initial Intensity of Electricity in Residential Energy Production	Constant	EIA
Initial Intensity of Natural Gas in Residential Energy Production	Constant	EIA
Initial Intensity of Oil in Residential Energy Production	Constant	EIA
Initial Intensity of Renewable Resources in Residential Energy Production	Constant	EIA
Residential Elasticity of Coal Demand to Coal Price	Constant	EIA
Residential Elasticity of Coal to Shock Price	Constant	EIA
Residential Elasticity of Electricity Demand to Electricity Price	Constant	EIA
Residential Elasticity of Electricity to GDP	Constant	EIA
Residential Elasticity of Natural Gas Demand to Natural Gas Price	Constant	EIA
Residential Elasticity of Natural Gas to Shock Price	Constant	EIA
Residential Elasticity of Oil to Shock Price	Constant	EIA
Residential Elasticity of Oil Demand to Oil Price	Constant	EIA
Residential Elasticity of Renewable Resources Demand to Renewable Resources Price	Constant	EIA
Residential Elasticity of Renewable Resources to Shock Price	Constant	EIA
Technology Effect on Renewable Resources Utilization	Constant	EIA
Time to Adapt Demand to Price Changes	Constant	Estimated based on historical data on demand and price

Functional Explanation

The Residential Energy Demand module represents energy demand in the residential sector, disaggregated into five energy sources: oil, natural gas, coal, renewable energy and electricity. Since every energy source is treated in the same way, for simplicity, only oil demand in the residential sector will be explained.

Normalized Residential Oil Demand

Figure 3: Sketch of the main factors influencing Residential Oil Demand



The variable *Normalized Residential Oil Demand* represents the final residential oil demand, which includes both the effect of technology and prices (on demand and substitution for other energy sources). It is calculated as the *Normalized Residential Oil Share of Energy Demand* multiplied by the *Total Residential Indicated Energy Demand*:

> normalized residential oil demand= normalized residential oil share of energy demand*total residential indicated energy demand

The *Total Residential Indicated Energy Demand* represents the residential energy demand calculated considering the effect of technology and the effect of price on demand. The effect of substitutability is not considered in the formulation of *indicated energy demand* because it does not influence the total demand, but only the allocation of the demand into the five different energy sources considered in this study. *Total Residential Indicated Energy Demand* is calculated as the sum of the five *indicated residential energy source demand*:

> total residential indicated energy demand= indicated residential coal demand+ indicated residential electricity net demand+ Indicated residential natural gas demand +indicated residential oil demand +indicated residential renewable resources demand

The *Normalized Residential Oil Share of Energy Demand* represents the fraction of energy demand in the residential sector that is oil demand. It accounts for both the effect of prices (on demand and substitution for other energy sources) and technology and it is calculated as *Residential Oil Demand* over *Total Residential Energy Demand*:

normalized residential oil share of energy demand= Residential Oil Demand/total residential energy demand

The *Total Residential Energy Demand* represents the energy demanded in the residential sector considering both the effect of technology and prices (on demand and substitution for other energy sources) on demand. It is equal to the sum of residential oil, coal, natural gas, electricity and renewable resources demand:

total residential energy demand= Residential Coal Demand+Residential Electricity Net Demand+Residential Natural Gas Demand+Residential Oil Demand+Residential Renewable Resources Demand

The *Residential Oil Demand* represents the oil demanded in the residential sector. It accounts for both effect of energy prices and technology. It is calculated as *Indicated Residential Oil Demand* multiplied by the oil price relative to the average energy price, all by the power of the *Residential Elasticity of Oil Demand to Oil Price*. A delay function is used to represent the time lag between price changes and energy demand shift.

Residential Oil Demand=DELAY N((indicated residential oil demand *Oil Pricebtu Substitutability^RESIDENTIAL ELASTICITY OF OIL DEMAND TO OIL PRICE), TIME TO ADAPT DEMAND TO PRICE CHANGES,(indicated residential oil demand*Oil Pricebtu Substitutability ^RESIDENTIAL ELASTICITY OF OIL DEMAND TO OIL PRICE), 3)

The *Indicated Residential Oil Demand* takes into account only the effect of technology and price on demand, and it does not consider the effect of energy price on substitutability. The *Indicated Residential Oil Demand* is calculated as GDP multiplied by *Indicated Residential Oil GDP Intensity*:

indicated residential oil demand= real gdp at market prices*indicated residential oil gdp intensity

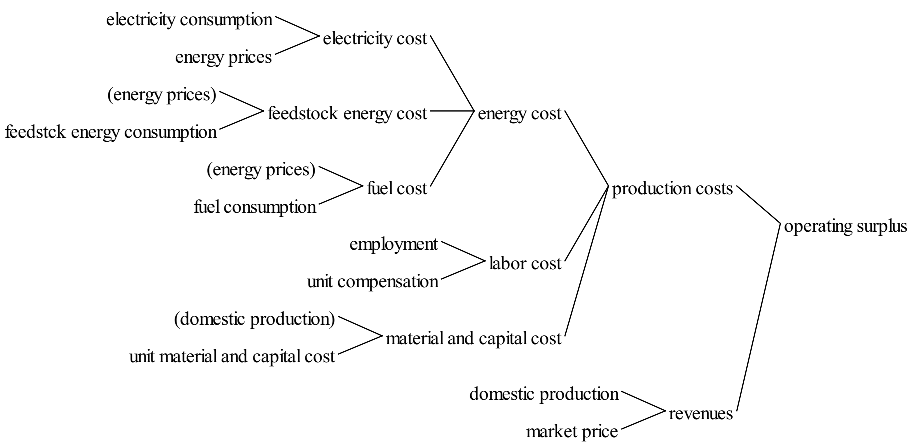
The *Indicated Residential Oil GDP Intensity* represents the oil intensity of GDP and it takes into account the effect of technology and energy price. This variable is calculated as the oil intensity of GDP in the residential sector divided by relative technology and by the *Effect of Oil Price on Energy Demand*, all to the power of the *Residential Elasticity of Oil Demand to Price*:

indicated residential oil gdp intensity= (INITIAL INDICATED RESIDENTIAL OIL GDP INTENSITY/relative resources technology[IND])/Effect Of Oil Price On Energy Demand ^ RESIDENTIAL ELASTICITY OF OIL DEMAND TO PRICE

Energy Intensive Industries

Cost Structure Module

Figure 4: Sketch of the main factors influencing Operating Surplus



Purpose and Perspective

The cost structure module calculates total production costs as the sum of energy, labor, capital and material costs. In addition, operating surplus and operating margin are calculated, using both total revenues and production costs.

Domestic production, both for domestic consumption and export, is the main endogenous input to the cost structure module. Domestic production uses GDP (exogenous input) and domestic market share, calculated in the Market module.

Explanation

Major Assumptions

- The cost structure given by the Annual Survey of Manufacturers is adopted (NAICS);
- MECS data are used to calculate the energy intensity for various energy sources (both off-site and feedstock); for future projections a 0.25% yearly improvement in energy efficiency is assumed;
- Operating surplus is calculated as total revenues (value of shipments) minus labor, capital, material and energy costs, as reported in the Annual Survey of Manufacturers.

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Average electricity cost per KWH	Time Series	NEMS (EIA – AEO 2008)
Coal price	Time Series	NEMS (EIA – AEO 2008)
Coke price	Time Series	NEMS (EIA – AEO 2008), calculated
Demand per unit of GDP	Time Series	ASM
Distillate fuel oil price	Time Series	NEMS (EIA – AEO 2008)
Employment per unit of output	Time Series	ASM, calculated
GDP deflator table	Time Series	NEMS (EIA – AEO 2008)
Internal energy production per unit of output	Time Series	MECS
LPG price	Time Series	NEMS (EIA – AEO 2008)
Market price	Time Series	ASM
Natural gas price	Time Series	NEMS (EIA – AEO 2008)
Non energy coal intensity	Time Series	MECS, calculated
Non energy coke intensity	Time Series	MECS, calculated
Non energy distillate fuel oil intensity	Time Series	MECS, calculated
Non energy LPG intensity	Time Series	MECS, calculated
Non energy natural gas intensity	Time Series	MECS, calculated
Non energy residual fuel oil intensity	Time Series	MECS, calculated
PC labor cost	Time Series	ASM
Residual fuel oil price	Time Series	NEMS (EIA – AEO 2008)
Unit material cost	Time Series	ASM
US GDP	Time Series	NEMS (EIA – AEO 2008)

Functional Explanation

Total US aluminum demand is calculated using GDP and aluminum intensity. The projection for GDP is taken from the Congressional Budget Office (CBO) and the Energy Information Administration (EIA). Aluminum intensity is calculated as GDP over aluminum demand.

> Total aluminum demand = US GDP(Time)*ALUMINUM DEMAND PER UNIT OF GDP(Time)

Domestic aluminum production, for domestic consumption and export, is equal to total aluminum demand multiplied by the market share of US aluminum producers.

Domestic aluminum production is disaggregated into primary and secondary production. Secondary production is assumed to be the residual factor for domestic production. The market share of primary production is calibrated according to assumptions provided by the industry association.

> Domestic primary aluminum production=total domestic aluminum production-domestic secondary aluminum production
>
> Domestic secondary aluminum production=scrap aluminum consumption share*total domestic aluminum production

The total production cost of aluminum production is calculated as the sum of labor, energy and capital and material costs.

> Aluminum total production cost=aluminum energy cost+aluminum labor cost+aluminum material and capital production cost

Labor costs are calculated as employment multiplied by the unit labor compensation. Total employment is obtained by multiplying domestic production by labor requirements per unit of output. Material and capital costs are calculated as unit cost multiplied by domestic primary aluminum production.

> Aluminum labor cost=total aluminum employment*ALUMINUM LABOR COST TABLE(Time)

Total energy costs are calculated as the sum of electricity and fuel costs, both for direct and feedstock energy use. Fuel (direct) and feedstock energy costs are calculated for various energy sources, including coal, coal coke, distillate fuel oil, residual fuel oil, LPG and natural gas. Demand for each specific energy source, such as natural gas, is calculated as primary aluminum production multiplied by natural gas intensity. Expenditure for such fuel is calculated by multiplying consumption by natural gas price.

> Aluminum fuel cost=aluminum coal consumption*COAL PRICE(Time)+aluminum distillate fuel oil consumption*DISTILLATE FUEL OIL PRICE(Time)+aluminum LPG consumption*LPG PRICE(Time)+aluminum natural gas consumption*NATURAL GAS PRICE(Time)+aluminum residual fuel oil consumption*RESIDUAL FUEL OIL PRICE(Time)+aluminum coke consumption*COKE PRICE(Time)

Electricity expenditure is calculated by multiplying consumption by price and accounts for internal production (which is subtracted from total energy demand).

> Total electricity demand for aluminum production=((domestic primary aluminum production)*ALUMINUM INDUSTRY ELECTRICITY INTENSITY(Time))-internal aluminum electricity production

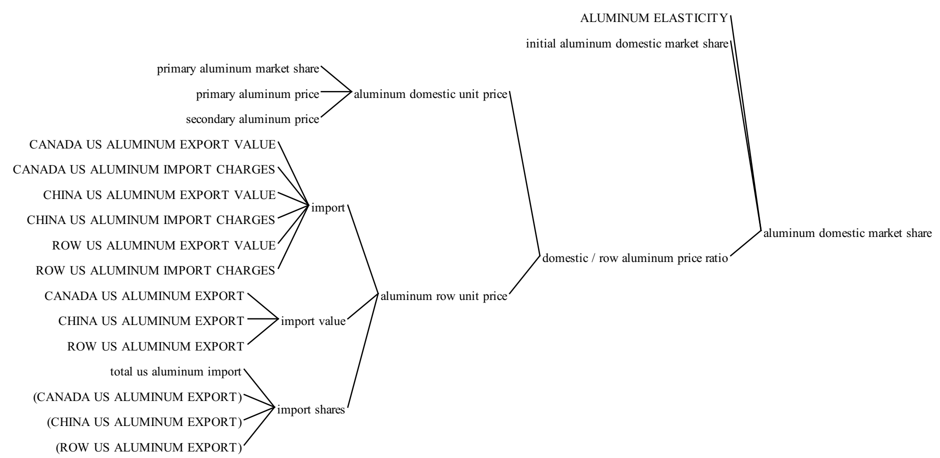
The operating surplus is calculated as total revenues (i.e. value of shipments) minus total production costs (i.e. labor, energy, capital and material cost). The operating margin is instead calculated as operating surplus over revenues.

Aluminum operating surplus=aluminum revenues-aluminum total production cost

A variety of indicators are also provided. These include total unit costs, as well unit labor, energy and material and capital cost. All monetary values are calculated both in nominal and real terms (in USD 2000).

Market Module

Figure 5: Sketch of the main factors influencing Aluminum Domestic Market Share



Purpose and Perspective

The market module calculates domestic market share using the ratio between domestic and international prices. International import prices are calculated using import quantities and customs values, plus import charges, for the main exporters to the US (e.g. Canada, Russia, Venezuela, Brazil, EU15, China and rest of the world, for the aluminum sector).

Domestic market share is the main endogenous variable calculated in the Market module. Market share is used to define domestic production (both for domestic consumption and export) out of total demand (for domestic consumption and export).

Domestic price is the main endogenous input for the market module, in the cost pass-along scenarios, calculated in the cost structure module.

Explanation

Major Assumptions

- Major exporters to the US are calculated using the Annual Survey of Manufacturers (ASM) and industrial trade associations, which include the American Iron and Steel Institute (AISI), the American Forest and Paper Association (AF&PA), the American Chemistry Council (ACC), and the Aluminum Association;
- Price differentials between domestic and foreign markets are assumed to be the main drivers for domestic market share;
- Domestic market share is calculated using the domestic/foreign price ratio and an elasticity parameter estimated using historical data from 1992 to 2007.

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Country US aluminum export	Time Series	ASM
Country US aluminum export value	Time Series	ASM
Country US aluminum import charges	Time Series	ASM
Elasticity of domestic production to price	Constant	ASM, estimated
Initial US domestic market share	Constant	ASM

Functional Explanation

The calculation of domestic market share accounts for a delay representing longer term contracts and the inertia of the system in spite of short term price changes. Market share is therefore calculated as initial market share multiplied by the delayed relative ratio of domestic/foreign prices, with respect of 1992, which is raised to the power of the elasticity estimated using historical data from 1992 until 2007 and further calibrated to obtain the best fit to data.

> Aluminum domestic market share = INITIAL US ALUMINUM DOMESTIC MARKET SHARE/(Delayed Relative Row And Us Aluminum Prices Ratio)^ALUMINUM ELASTICITY

The value for elasticity is obtained through optimization, using a linear programming function provided by Vensim. This value is then revised to improve fitting with the latest historical data points available, to represent the longer term trend of domestic market share and also to better incorporate the recent effect of increasing prices on market share.

Aluminum	Optimization (1992-2006) Model	0.87 1	 Trend accuracy (2004 - 2006)
Steel	Optimization (1992-2006) Model	0.77 1	 Trend accuracy (1997 - 2002)
Paper	Optimization (1992-2006) Model	0.62 0.75	 Trend accuracy (2000-2004)
Petrochemicals	Optimization (1997-2006) Model	0.1 0.2	 Trend accuracy (2002 - 2006)
Alkalise & Chlorine	Optimization (1997-2006) Model	0.125 0.15	 Trend accuracy (lack of data for the years1992 through 1996)

The average international import price is calculated as the weighted average of country export prices to the US and export quantities to the US. Country export prices to the US are calculated by dividing the sum of custom value of export and import charges by export quantities.

Aluminum row price=

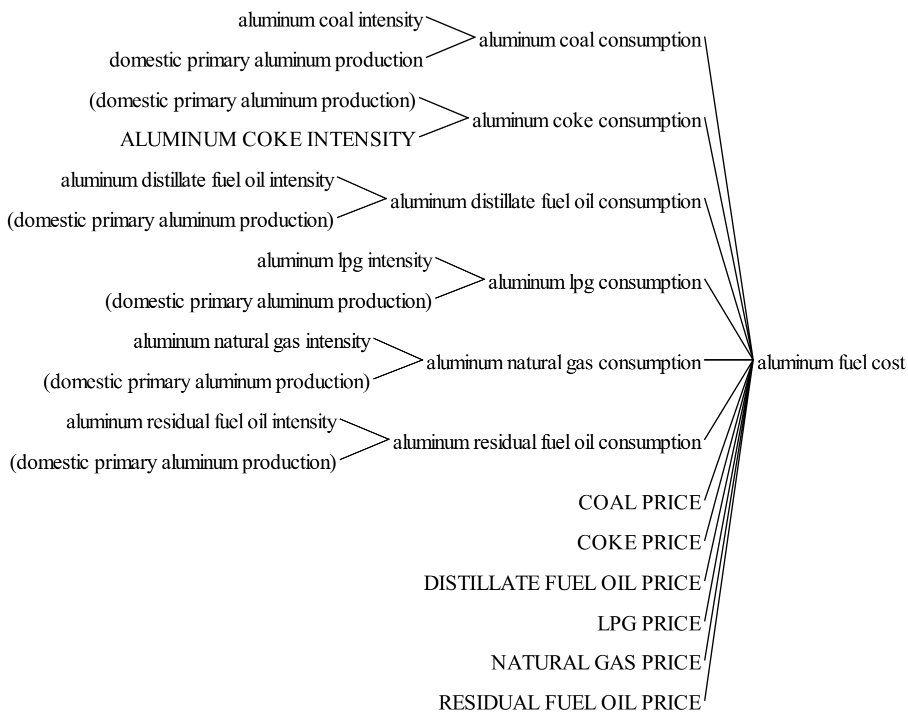
brazil us aluminum export price*brazil us aluminum export share +
canada us aluminum export price*canada us aluminum export share +
china us aluminum export price*china us aluminum export share +
EU15 us aluminum export price*EU15 us aluminum export share +
russia us aluminum export price*russia us aluminum export share +
venezuela us aluminum export price*venezuela us aluminum export share + row us aluminum export price*row us aluminum export share

Canada us aluminum export price=

(CANADA US ALUMINUM EXPORT VALUE(Time) +
CANADA US ALUMINUM IMPORT CHARGES(Time)) /
CANADA US ALUMINUM EXPORT(Time)

Investment Module

Figure 6: Sketch of the main factors influencing Aluminum Fuel Cost



Purpose and Perspective

The investment module is used to estimate the potential impact of investment in energy efficiency on total production cost and profitability. Fuel intensity (demand per unit of production) is calculated with MECS data and projected using various assumptions including: (1) baseline technological development (i.e. 0.25% a year), (2) 5% annual increase in energy efficiency and (3) energy efficiency improvement that compensates the increase in energy cost correspondent to the three pricing scenarios considered (i.e. S.1766, S.2191 and S.2191 with no offsets).

Energy demand is calculated for coal, distillate fuel oil, LPG, natural gas, residual fuel oil and coal coke.

Constants and Table functions

Variable Name	Type of	Source for Estimation

	Variable	
Coal intensity	Time Series	MECS, calculated
Coke intensity	Time Series	MECS, calculated
Distillate fuel oil intensity	Time Series	MECS, calculated
Electricity intensity	Time Series	MECS, calculated
LPG intensity	Time Series	MECS, calculated
Natural gas intensity	Time Series	MECS, calculated
Residual fuel oil intensity	Time Series	MECS, calculated

Electrified Rail and Transportation Sector

Purpose and Approach

The purpose of the Transportation Energy Demand module is to calculate and represent energy demand in the transportation sector. This includes air, road and rail travel. Transportation energy demand is disaggregated into four energy sources, following the EIA classification contained in the Annual Energy Review.

Explanation

Major Assumptions

- Four energy sources are considered (renewable, natural gas, oil, electricity);
- Oil is disaggregated into gasoline and jet fuel;
- Energy demand is influenced by energy prices (energy demand of a specific source is influenced by its price) and technology;
- Relative price of one energy source with respect to the other sources only generates shifts from one source to the others;
- Electricity demand form urban and commuter rail is mainly influenced (at least in the early years) by the assumed build up of infrastructure.

Input Variables[11]

Variable Name	Module of Origin
Electricity Price Substitutability	Energy Prices
Indicated Transportation Gasoline Demand	Energy Demand: Transportation Fleet
Natural Gas Multiplier for Shock Price	Effect of Price on Demand
Natural Gas Price Substitutability	Energy Prices
Oil Multiplier for Shock Price	Effect of Price on Demand
Oil Price Substitutability	Energy Prices
Real GDP at Market Prices	Investment
Relative Resources Technology	Technology
Renewable Resources Price Substitutability	Energy Prices
Time to Adapt Demand to Price Changes	Residential Energy Demand
Total oil Demand in QDBTU	U.S. Fossil Fuels Emissions

Output Variables

	Module of Destination		
Variable Name	Same Sector	Other Energy Sectors	Other Sectors
Normalized Transportation Electricity Net Demand		Demand and Import: Electricity	
Normalized Transportation Natural Gas Demand		Demand and Import: Natural Gas	
Normalized Transportation Oil Demand		Demand and Import: Oil	
Normalized Transportation Renewable		Demand and Import: Renewable	

[11] Constant and table functions in the transportation sectors are similar to the ones presented for the residential sector.

Resources Demand		Resources	

Functional explanation

Indicated Transportation Oil Demand

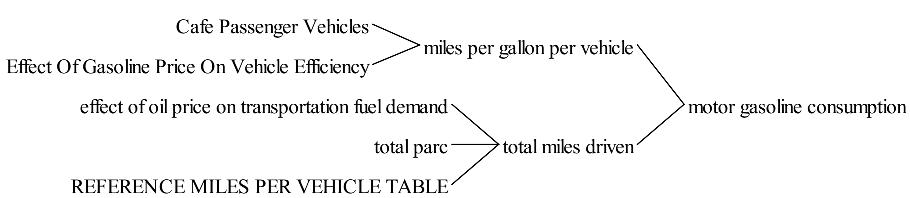
The main difference between oil demand in the transportation and other sectors consists in the utilization of a disaggregated oil demand for gasoline and jet fuel and in the direct subtraction of oil replaced by increased electricity use from urban and freight rail (with a ratio equal to 20:1, which assumes that 20 Btu of oil can be substitute with 1 Btu of electricity). While demand for jet fuel is calculated as any other source of energy (see Residential Energy Demand), gasoline demand is calculated in a more elaborated way, which is introduced below. The *Indicated Transportation Oil Demand* is therefore equal to the sum of *Indicated Jet Fuel Demand* and *Indicated Transportation Gasoline Demand*:

> indicated transportation oil demand= indicated jet fuel demand +
> indicated transportation gasoline demand

Transportation gasoline demand is calculated based on the total number of cars, their average miles driven per year and their average consumption per gallon. By doing so three main drivers of gasoline demand are taken in to consideration: population (which determines the number of cars in the nation), technology (which influences the average car consumption of gasoline), and culture (which affects the average miles driven per year, the willingness to live close to the workplace or the necessity to live outside the metropolitan area, etc.) Apart from motor gasoline demand, other liquid fuels demanded by the transportation sector are considered and jet fuel is added to calculate the total oil demand.

Indicated Transportation Gasoline Demand

Figure 7: Sketch of the main factors influencing Motor Gasoline Consumption



The *Indicated Transportation Gasoline Demand* represents the indicated total gasoline demand, excluding jet fuel, which is demanded in the US. It is calculated as the sum of *Indicated Motor Gasoline Demand in BTU* and *Transportation Other Fuel Demand*.

The *Indicated Motor Gasoline Demand in BTU* is equal to the *Motor Gasoline Consumption*, converted from Gallons to BTU by using a *BTU Gallon Conversion Factor*.

The *Motor Gasoline Consumption* represents the potential consumption of gasoline when substitutes are not taken into consideration. It is equal to *Total Miles Covered* divided by *Miles per Gallon per Vehicle*:

> motor gasoline consumption=total miles covered/miles per gallon per vehicle

Total Miles Covered represents the total amount of miles driven during one year by all the cars in the nation. It is calculated as the product between *Total Car Parc* and *Mileage per Vehicle*, divided by the effect of oil price on miles covered:

> total miles covered= total car parc*MILEAGE PER VEHICLE(Time)/ effect of oil price on transportation fuel demand

The *Total Car Parc*, which represents the total stock of cars owned in the country, is calculated as the *Average Number of Vehicle per Person* multiplied by the *Total Population* and divided by the effect of oil prices:

> total car parc=total population*Average number of vehicles per person(Time)/effect of oil price on transportation fuel demand

Miles per Gallon per Vehicle represents the fuel economy of the transportation sector, in other words the number of miles that a vehicle can run with a gallon. It is calculated as the sum of fuel efficiency for passenger vehicle multiplied by their share of the car parc and a reference (flat) fuel economy curve for non-passenger vehicles (e.g. commercial and freight), multiplied by their share of total US vehicle stock. This formulation is used to disaggregate improvement in fuel economy for passenger vehicles (which are included in the CAFE provisions approved in late 2007) and the rest of the transportation sector. The positive effect of gasoline prices on fuel economy is also accounted for:

> miles per gallon per vehicle= IF THEN ELSE(Time<2006, CAFE HISTORY(Time), (Cafe Passenger Vehicles*VEHICLE PASSENGER SHARE OF VEHICLE PARK+MILES PER GALLON PER VEHICLE FUNCTION(Time)*(1-VEHICLE PASSENGER SHARE OF VEHICLE PARK))*Effect Of Gasoline Price On Vehicle Efficiency)

The *Effect of Gasoline Price on Vehicle Efficiency* represents the technological improvement in car gasoline consumption generated by an increase in gasoline price. It is calculated as a third order delay of the *Relative Gasoline Price* raised to the power of the *Elasticity of Efficiency to Gasoline Price*. A five years delay in the creation and commercialization of more efficient technology is also considered:

> effect of gasoline price on vehicle efficiency= DELAY N(relative gasoline retail price^ elasticity of efficiency to gasoline price, time to implement new efficiencies , 1, 3)

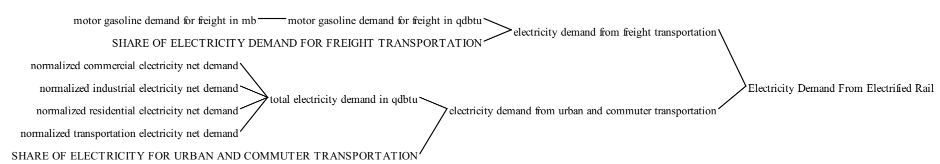
Renewable Resources substitutability price: gasohol and ethanol

The substitutability price of renewable resources is calculated as the *Gasohol and Ethanol Price Substitutability*. It is equal to oil price substitutability multiplied by one minus the *Perceived Percentage of Taxes on Gasoline Retail Price* (given the fact that both Ethanol and Gasohol are not taxed by the U.S. Government) and by 0.85, which is the fraction of oil contained in one gallon of alcohol mixture fuel such as E15. The remaining fraction of price is obtained by multiplying the *Renewable Resources Price Substitutability* by 0.15:

> gasohol and ethanol price substitutability=Oil Pricebtu Substitutability*(1-Perceived Percentage Of Taxes On Gasoline Retail Price)*0.85+Renewable Resources Price Substitutability*0.15

Electricity Demand from Urban and Freight Rail

Figure 8: Sketch of the main factors influencing Electricity Demand from Electrified Rail



Electricity demand for Freight Rail is calculated using the assumption that 85% of existing tracks will be electrified by 2030. A linear growth is assumed to take pace between 2010 and 2025, when electrification reaches 80%, to grow to 85% by 2030 and remain flat for the remainder of the simulation. Liquid fuel consumption for freight rail is calculated using the variable *Normalized Transportation Liquid Fuel Demand*, endogenously calculated, and its share of freight rail, which equals 16.32% in 2007 and is assumed to remain constant. Since oil consumption is expressed in million barrels, it is converted into BTU and then normalized using the ratio 20:1 to estimate what is the actual equivalent of electricity needed to replace oil consumption. A delay is introduced to simulate more realistically the ramping up electrification of rail during the first years of track conversion:

electricity freight transportation= DELAY N((motor gasoline demand for freight in qdbtu/20)*SHARE OF ELECTRICITY FOR FREIGHT TRANSPORTATION(Time), 6, 0, 1)

Electricity demand for Urban Rail is calculated using the assumption that there will be a 28% annual increase in electrical demand, created by new Urban Rail lines, higher density on existing Urban Rail Lines and electrifying current diesel commuter lines. This corresponds to an increase in electrical demand by Urban Rail of 0.05% (which currently equals 0.19%) of total demand per year. Electricity demand from urban rail is calculated as:

electricity urban and commuter transportation= total electricity demand in qdbtu*SHARE OF ELECTRICITY FOR URBAN AND COMMUTER TRANSPORTATION(Time)

ROW Energy Demand: Canada, Mexico, China and India

Purpose and Approach

The Rest of the World energy demand modules represent the demand of fossil fuel in Canada, Mexico, China and India in addition to electricity demand in Canada and Mexico. Canada and Mexico are incorporated in the North America model only, while China and India energy demand can be found in the US model as well.

Explanation

Major Assumptions

- GDP is influenced by energy prices;
- Fossil fuel demand is determined by GDP, population, technology, and fossil fuels prices.

Input Variables (China module)

Variable Name	Module of Origin
Real row oil price per MBTU	ROW Resources Price and Cost: Oil
Real row coal price per MBTU	ROW Resources Price
Real row natural gas price per MBTU	ROW Resources Price
World oil demand	Demand and Import: Oil
World Coal demand	Demand and Import: Coal
World natural gas demand	Demand and Import: Natural Gas

Output Variables (China module)

	Module of Destination		
Variable Name	In the Same Sector	In Other Energy Sectors	In Other Sectors
China coal demand in Mst		Demand and Import: Coal	
China natural gas demand in Bcf		Demand and Import: Natural Gas	
China oil demand in Mb		Demand and Import: Oil	
Relative international coal price		Demand and Import: Coal	
Relative international natural gas price		Demand and Import: Natural Gas	
Relative international oil price		Demand and Import: Oil	
World Coal Demand in Qdbtu		ROW Energy Demand: India	
World Natural Gas Demand in Qdbtu		ROW Energy Demand: India	
World Oil Demand in Qdbtu		ROW Energy Demand: India	

Constants and Table functions (China module)

Variable Name	Type of Variable	Source for Estimation
China future GDP growth rate	Time Series	Estimated
Elasticity of China Coal demand to Coal Price	Constant	Estimated
Elasticity of China Natural Gas demand to Natural Gas Price	Constant	Estimated
Elasticity of China Oil demand to Oil Price	Constant	Estimated
Elasticity of china value added to coal price	Constant	Estimated
Elasticity of china value added to Natural Gas price	Constant	Estimated

Elasticity of china value added to oil price	Constant	Estimated
Initial China Coal intensity on GDP	Constant	EIA
Initial China GDP	Constant	EIA
Initial China Natural Gas intensity on GDP	Constant	EIA
Initial China Oil intensity on GDP	Constant	EIA
Reference relative international coal price	Constant	Estimated
Reference relative international natural gas price	Constant	Estimated
Reference relative international oil price	Constant	Estimated
Relative china technology	Time Series	Estimated

Functional Explanation

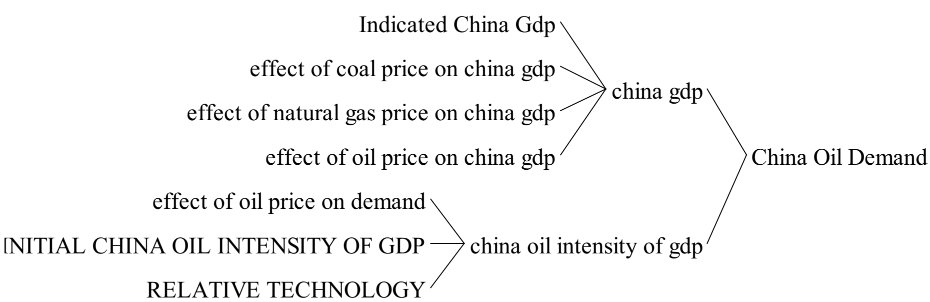
GDP

The Gross Domestic Product (GDP) is generally used to calculate energy demand for all countries analyzed. In the case of Canada, Mexico, China and India, GDP is partially exogenous. Its growth is represented by a time series and divided by the effect of energy prices, and it is used to calculated Indicated *Country* GDP.

> real gdp growth rate[country]= REAL GDP GROWTH RATE TABLE[country](Time)/relative weighted average energy price^ ELASTICITY OF GDP TO ENERGY PRICES[country]

Energy Demand: China and India

Figure 9: Sketch of the main factors influencing China Oil Demand



The main factors used to calculate energy demand are GDP, energy prices, population and technology (energy efficiency). In the case of China and India specifically it is assumed that GDP is the main factor driving energy demand, therefore fossil fuel demand is calculated by multiplying gross domestic product by fossil fuel intensity on GDP:

> China Oil Demand= DELAY N(china oil intensity on gdp*china gdp,1,3.81,3)

China Coal Demand= DELAY N(china coal intensity on gdp*china gdp,1,12.3,3)

China Natural Gas Demand= DELAY N(china gdp*china natural gas intensity on gdp,1,0.581,3)

A delay of one year is used to represent the time lag existing between changes in GDP to influence energy demand.

The fossil fuel intensity on GDP for China and India is calculated as its initial value (1980) multiplied by relative fossil fuel price raised to the power of the elasticity of fossil fuel demand to price, all divided by the relative value of fossil fuel technology:

china oil intensity on gdp= (INITIAL CHINA OIL INTENSITY ON GDP*relative international oil price^ELASTICITY OF CHINA OIL DEMAND TO OIL PRICE)/RELATIVE CHINA TECHNOLOGY(Time)

Energy Demand: Canada and Mexico

Concerning Canada and Mexico, GDP and energy prices are used as the main factors influencing oil and coal demand. Population is an additional variable influencing natural gas and electricity demand, which are to a lesser extent influenced by GDP and more dependent on population and residential buildings.

Oil and coal demand are therefore calculated as the multiplication of initial demand in 1980 by relative real GDP, all divided by relative energy prices. An elasticity value regulating the response of energy demand to GDP and energy prices is calculated:

oil demand[country]= INITIAL OIL DEMAND[country]*(relative real gdp[country]^ELASTICITY OF OIL DEMAND TO GDP)/relative row oil price^ELASTICITY OF OIL DEMAND TO OIL PRICE

Natural gas and electricity demand are calculated using population, as mentioned above. While natural gas demand is assumed to be influenced by GDP, population, and natural gas price, electricity is calculated using energy efficiency improvement instead of prices, being characterized by fast technological improvement not directly connected to increasing prices and being less sensitive to price changes.

electricity demand[country]= INITIAL ELECTRICITY DEMAND[country]*relative real gdp[country]^ELASTICITY OF ELECTRICITY DEMAND TO GDP[country]*relative total population[country]/relative energy efficiency

Energy Demand: Ecuador

As in the case of Canada and Mexico, GDP, energy prices and technology are used as the main factors influencing energy demand. Population is again used when calculating electricity demand. Total oil and natural gas are calculated both for direct use and for electricity generation. A subscript is introduced to distinguish between these two variables: electric and non-electric.

Natural gas demand is calculated as the multiplication of initial demand by relative real GDP, all divided by technology and relative energy prices. An elasticity value regulating the response of energy demand to GDP and energy prices is calculated:

> sectoral natural gas demand[NON ELECTRIC]=
> (INITIAL SECTORAL NATURAL GAS DEMAND[NON ELECTRIC]*relative gdp ^ SECTORAL ELASTICITY OF NATURAL GAS CONSUMPTION TO GDP/energy consumption technology)/
> Effect Of Natural Gas Sectoral Price On Demand[NON ELECTRIC]^
> SECTORAL ELASTICITY OF NATURAL GAS DEMAND TO PRICE[NON ELECTRIC]

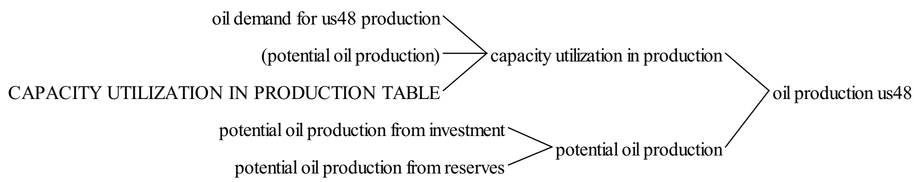
Natural gas demand for electricity production is calculated using total gross electricity demand, accounting for retails sales, distribution, transmission and generation losses, minus all available output from hydro and renewables. The allocation of thermal electricity generation into different energy sources is mainly driven by their prices and production capacity in place.

> sectoral natural gas demand[ELECTRIC]= fossil fuel consumption for electricity production[NATURAL GAS]/MWH TO BCF
>
> fossil fuel consumption for electricity production[NATURAL GAS]= required electricity generation from fossil fuels*fossil fuel share of electricity generation[NATURAL GAS]

Energy Supply

Conventional Oil Production

Figure 10: Sketch of the main factors influencing US48 Oil Production



Purpose and Approach

The Oil Production module represents the oil production in the U.S. Lower 48 States by considering production capacity from investment and availability of resources and reserves. The purpose of the Oil Production module is to calculate oil production and to keep track of both national oil resources and reserves. The approach used for modeling fossil fuels and non-fuels minerals resource in place is based upon the main groups of the McKelvey box (Figure 12): undiscovered resources and identified reserves. The structure of the model borrows from the research carried out by Davidsen, Sterman and Richardson (Davidsen, Sterman and Richardson, 1988 and 1990).

Alaskan oil production, natural gas and coal production modules, both domestic and international, are built on the structure of the domestic oil production, exploration and development modules. These are merged into a larger module that represents the whole production process for of the fossil fuel considered. Capital and technology are developed in separate modules.

Explanation

Major Assumptions

- Oil resource is finite;
- Exploration and production, separately, determine the availability of recoverable resources for production;

Input Variables

Variable Name	Module of Origin
Delayed Oil fraction developable	Production: Oil Technology
Investment in Oil Production	Energy Investment: Oil
Oil development rate	Production: Oil Development
Oil Discovery Rate	Production: Oil Exploration
Oil Fraction Discoverable	Production: Oil Technology
Oil Fraction Recoverable	Production: Oil Technology
Oil Demand for US48 Production	Demand and Import: Oil

Output Variables

	Module of Destination		
Variable Name	In the Same Sector	In Other Energy Sectors	In Other Sectors
Oil Developable Resources Remaining	Production: Oil Development		
Oil production in MB		Demand and import: Oil	
Oil Total Discoverable Resources Remaining	Production: Oil Exploration		
Oil total recoverable reserve remaining		Resources Price and Cost: Oil	
Oil total resource			

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Average capital life time for oil infrastructure	Constant	Estimated
Capacity Utilization in Production table	Time series	Estimated
Days in a year	Constant	Estimated
Effect of technology on productivity of investment in oil production table	Time series	Estimated
Initial Oil Cumulative Production	Constant	Data on energy (EIA)
Initial Oil Proved Reserve	Constant	Data on energy (EIA)
Initial Oil Unproved Resources	Constant	Data on energy (EIA)
Oil Production Delay	Constant	Estimated
Oil Reference Reserve Production Ratio	Constant	Estimated
Oil total resource	Constant	Data on energy (EIA)
Time to Average Oil Production	Constant	Estimated

Functional Explanation

The recovery (production) of fossil fuels (oil, gas, and coal) is modeled using the structure illustrated in Figure 11. In the case of fossil fuels production for the US and the rest of the world (excluding Canada and Mexico) two flows are represented for discovery activity: exploration and development.

Figure 11: Structure of the Energy Supply Model for Fossil Fuels

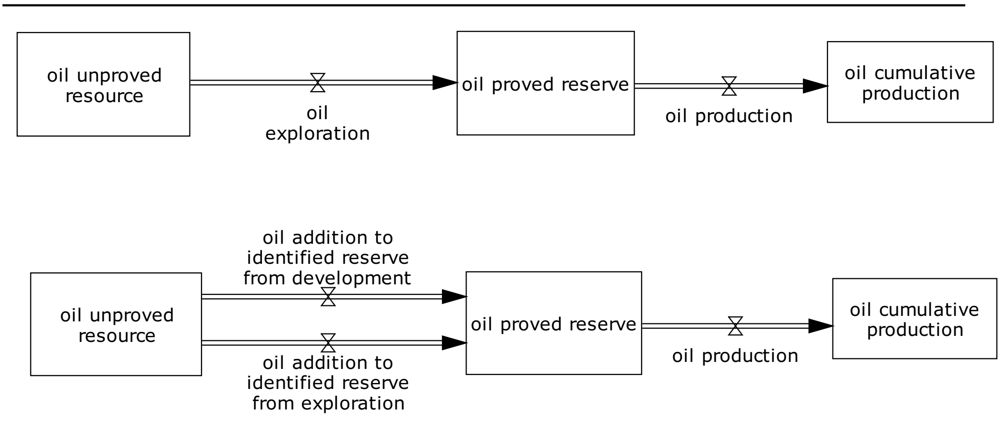
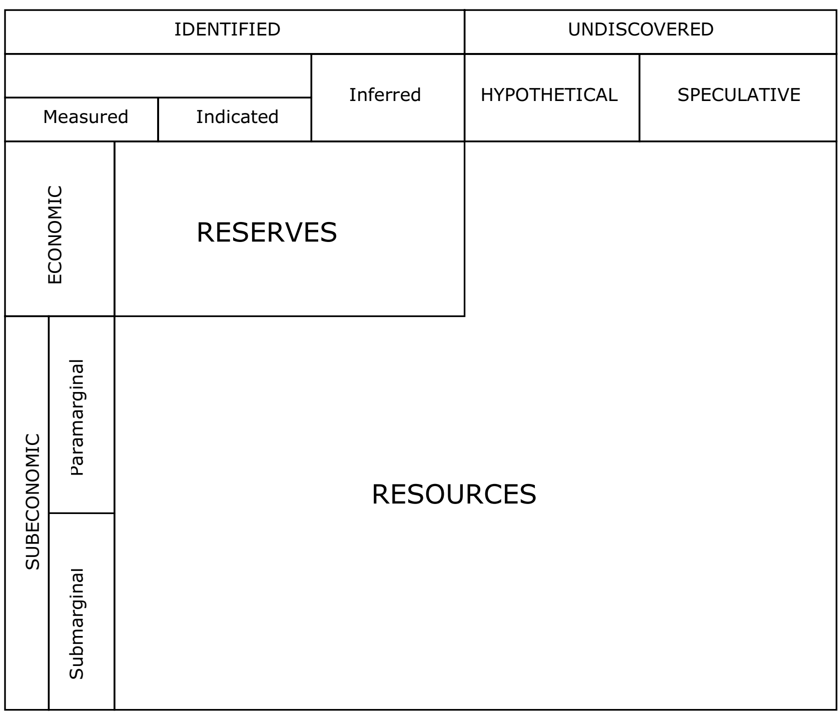


Figure 12: The McKelvey box Defining Terms Used by Resource Geologists and Economists



Geologists and economists categorize both fuel and non-fuel as illustrated in Figure 12. In this figure, economic feasibility increases from bottom to top, and geologic assurances increase from left to right. Resources can be economic or sub economic, identified or undiscovered. Reserves are the part of resources that are both economic and identified.

Reserves changes are defined by exploration (i.e. discovery: exploration and development) and production (i.e. recovery). Discovery activities shift the line between identified and undiscovered resources. Recovery activities shift the line between economic and sub economic. Discovery reduces resources, while production reduces reserves and adds to cumulative production. Both technology (discovery, development and recovery) and price determine the effectiveness of exploration and recovery activities.

Domestic oil production

The U.S. 48 oil production is calculated as potential oil production multiplied by capacity utilization in production:

> oil production in mb= oil potential production*capacity utilization in production

The variable *Capacity Utilization in Production* is equal to the table *Capacity Utilization in Production Table*, using oil demand in the lower 48 as input, then divided by potential oil production:

> capacity utilization in production= CAPACITY UTILISATION IN PRODUCTION TABLE(oil demand for us48 production/oil potential production)

Potential Oil Production is influenced by investments in infrastructure and by availability of recoverable reserve, and it is calculated as the minimum between *Potential Oil Production from Investment* and *Potential Oil Production from Reserves*:

> potential oil production= MIN(potential oil production from investment, potential oil production from reserves)

The variable *Potential Oil Production from Investment* is calculated by multiplying investment in oil production by its productivity, which is influenced by the amount of recoverable reserve remaining:

> potential oil production from investment= Effective Investment In Oil Production*productivity of investment in oil production

Potential Oil Production from Reserves is calculated as *Total Oil Recoverable Reserve Remaining* over a reference value for the reserve production ratio. The former is influenced by technology (fraction recoverable), cumulative addition to identified reserves and cumulative production:

total oil recoverable reserve remaining= oil cumulative addition to identified reserves*oil fraction recoverable-Oil Cumulative Production

The variable Oil Cumulative Addition to identified Reserves is equal to proved reserve plus cumulative production.

Conventional Oil Exploration

Purpose and Approach

The Oil Exploration module represents oil discovery from exploration. Productivity of investment in exploration, through availability of resource, and markup of the oil market, determine the oil discovery rate.

Explanation

Major Assumptions

- Productivity of investment in exploration, through availability of resource, and markup of the oil market, are the main factors determining the oil discovery rate.

Input Variables

Variable Name	Module of Origin
Oil total resource	Production: Oil
Oil Total Discoverable Resources Remaining	Production: Oil
Relative Oil Markup	Energy Markup

Output Variables

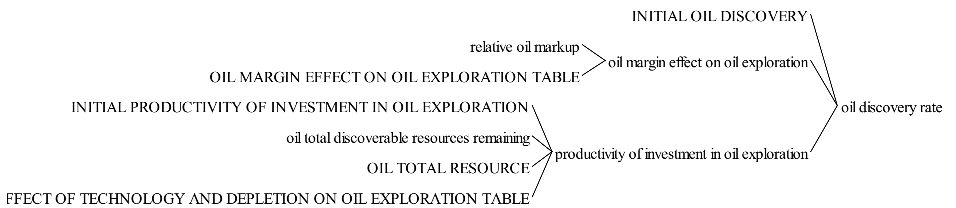
	Module of Destination		
Variable Name	In the Same Sector	In Other Energy Sectors	In Other Sectors
Oil discovery rate	Production: Oil		

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Effect of Technology and Depletion on Oil Exploration Table	Time series	Estimated
Elasticity of exploration on oil margin	Constant	Estimated
Initial Oil Discovery	Constant	EIA
Initial Productivity of Investment in Oil Exploration	Constant	Estimated
Oil Margin effect on Oil exploration table	Time series	Estimated

Functional Explanation

Figure 13: Sketch of the main factors influencing Oil Discovery Rate



The *Oil Discovery Rate* is calculated by considering initial discovery rate, effect of economic profitability of the oil market and productivity of the operation of exploration:

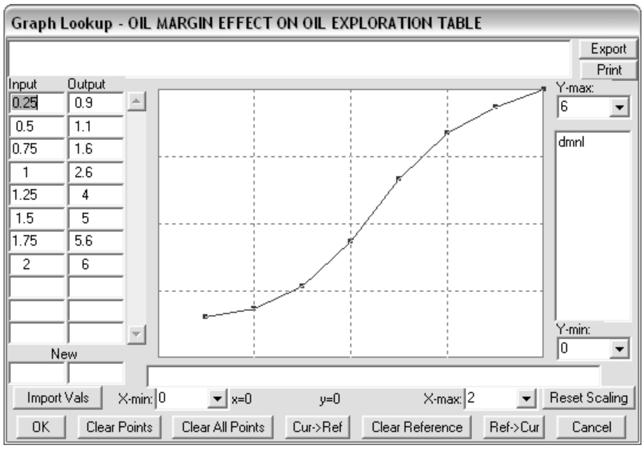
> oil discovery rate= INITIAL OIL DISCOVERY *oil margin effect on oil exploration*relative productivity of investment in oil exploration

The variable *Productivity of Investment in Exploration* is calculated based on the ratio *Oil Total Discoverable Resources Remaining* over *Oil Total Resource*.

The effect of markup on oil discovery is calculated by using the *Relative Oil Markup* as input for the *Oil Margin Effect on Oil Exploration Table*, all raised to the power of the *Elasticity of Exploration on Oil Margin*:

> oil margin effect on oil exploration= OIL MARGIN EFFECT ON OIL EXPLORATION TABLE(relative oil markup)^ELASTICITY OF EXPLORATION ON OIL MARGIN

Figure 14: Assumed relationship between oil margin and exploration activity



Conventional Oil Development

Purpose and Approach

The Oil development module represents oil discovery from development. Productivity of investment in development, through availability of both resource and reserve, and markup of the oil market, determine the oil development rate.

Explanation

Major Assumptions

- Productivity of investment in development, through availability of both resource and reserve, and markup of the oil market, are the main factors determining the oil development rate.

Input Variables

Variable Name	Module of Origin
Oil developable resources remaining	Production: Oil
Oil total resource	Production: Oil
Oil unproved resource	Production: Oil
Relative oil markup	Energy Markup

Output Variables

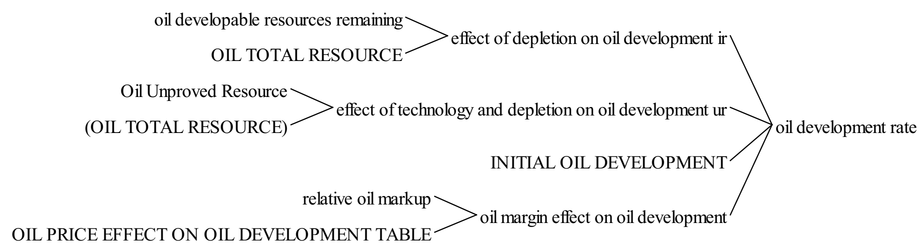
	Module of Destination		
Variable Name	In the Same Sector	In Other Energy Sectors	In Other Sectors
Oil development rate	Production: Oil		

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Effect of Depletion on Oil Development table IR	Time series	Estimated
Effect of Technology and Depletion on Oil Development table	Time series	Estimated
Initial Productivity of Investment in Oil Development	Constant	Estimated
Initial Oil Development	Constant	EIA
Oil price effect on Oil development table	Time series	Estimated

Functional Explanation

Figure 15: Sketch of the main factors influencing Oil Development Rate



The *Oil Development Rate* is calculated by considering initial development rate, effect of economic profitability of the oil market and productivity of the operation of development:

> oil development rate= INITIAL OIL DEVELOPMENT*oil price effect on oil development*relative productivity of investment in oil development

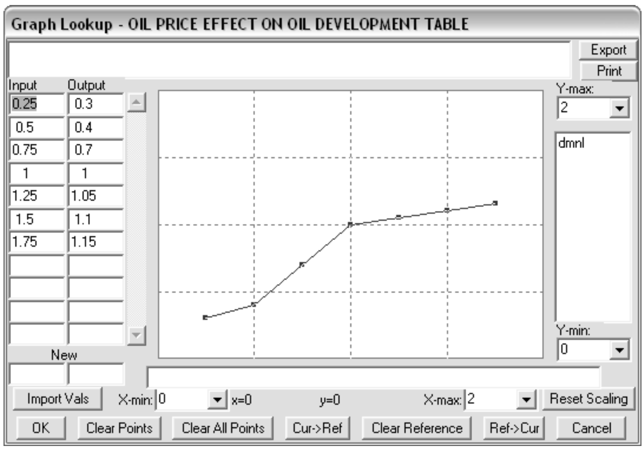
The variable *Productivity of Investment in Development* is calculated based on the ratio *Oil Developable Resources Remaining* over *Oil Total Resource* (to take into account the effect discovered reserve on additional development activity) and the ratio *Oil Unproved Resource* over *Oil Total Resource* (in order to consider the effect of undiscovered resource on development).

> effect of depletion on oil development ir= EFFECT OF DEPLETION ON OIL DEVELOPMENT TABLE IR(oil developable resources remaining/OIL TOTAL RESOURCE)
>
> effect of technology and depletion on oil development= EFFECT OF TECHNOLOGY AND DEPLETION ON OIL DEVELOPMENT TABLE(Oil Unproved Resource/OIL TOTAL RESOURCE)

The effect of markup on oil development is calculated by using the *Relative Oil Markup* as input for the *Oil Margin Effect on Oil Exploration Table*, all raised to the power of the *Elasticity of Exploration on Oil Margin*:

oil margin effect on oil development= OIL PRICE EFFECT ON OIL DEVELOPMENT TABLE(relative oil markup)

Figure 16: Assumed relationship between oil margin and development activity



Conventional Oil Technology

Purpose and Approach

The Oil Technology module represents technology development in the oil sector concerning exploration (discovery and development) and production (recovery). Cumulative investment in technology is used to calculate the fraction discoverable, developable and recoverable of respectively oil resource and reserve.

Explanation

Major Assumptions

- Technology improvement is influenced by investment.

Input Variables

Variable Name	Module of Origin
Investment in Oil Exploration	Energy Investment: Oil
Investment in Oil Production	Energy Investment: Oil

Output Variables

Variable Name	Module of Destination		
	In the Same Sector	In Other Energy Sectors	In Other Sectors
Delayed Oil fraction developable	Production: Oil		
Oil Fraction Developable	Production: Oil		
Oil Fraction Discoverable	Production: Oil		
Oil Fraction Recoverable	Production: Oil		

Constants and Table functions

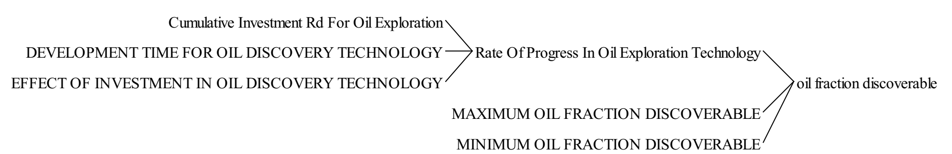
Variable Name	Type of Variable	Source for Estimation
Cumulative Investment 1970	Constant	Estimated
Development Time for Oil Discovery Technology	Constant	Estimated
Development Time for Oil Recovery Technology	Constant	Estimated
Effect of Investment in Oil Discovery Technology	Constant	Estimated
Effect of Investment in Oil Recovery Technology	Constant	Estimated
Maximum Oil Fraction Developable	Constant	Estimated
Maximum Oil Fraction Discoverable	Constant	Estimated
Maximum Oil Fraction Recoverable	Constant	Estimated
Minimum Oil Fraction Developable	Constant	Estimated
Minimum Oil Fraction Discoverable	Constant	Estimated
Minimum Oil Fraction Recoverable	Constant	Estimated

Functional Explanation

The Oil Technology module produces three main outputs: fraction discoverable, developable and recoverable. Those variables are calculated based on cumulative investment in oil exploration and production and represent the cumulative improvement of discovery, development and recovery technology.

Fraction Discoverable, Developable and Recoverable

Figure 17: Sketch of the main factors influencing Oil Fraction Discoverable



The fraction discoverable of oil in place represents the percentage of oil that can be discovered with respect to the total amount of resource in place. It is calculated as the minimum fraction discoverable, plus the difference between maximum and minimum fraction discoverable, all multiplied by the ratio progress in exploration technology over the same value increased by one:

> Oil fraction discoverable= MINIMUM OIL FRACTION DISCOVERABLE+ (MAXIMUM OIL FRACTION

```
    DISCOVERABLE-MINIMUM OIL FRACTION
    DISCOVERABLE)*(Rate Of Progress In Oil Exploration
    Technology/(Rate Of Progress In Oil Exploration Technology+1))
```

The *rate of progress in oil exploration technology* is calculated as the cumulative investment in oil exploration multiplied by the effect of investment in oil discovery technology. A delay function is introduced to consider the time need to develop and implement new technology.

```
Rate Of Progress In Oil Exploration Technology= DELAY N(
    EFFECT OF INVESTMENT IN OIL DISCOVERY
    TECHNOLOGY*Cumulative Investment Rd For Oil Exploration,
    DEVELOPMENT TIME FOR OIL DISCOVERY
    TECHNOLOGY, 3.701, 3)
```

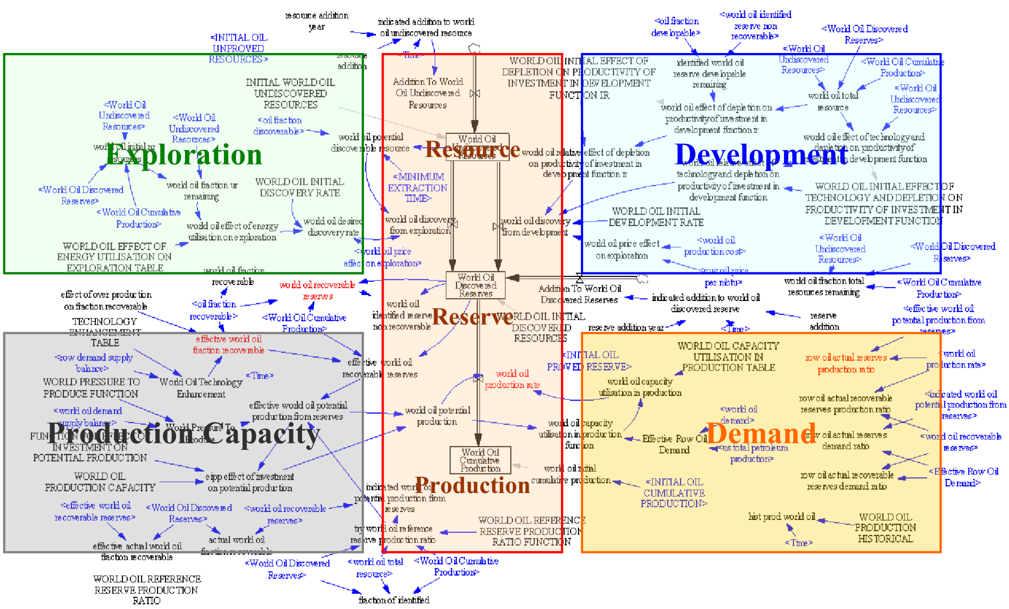
The fraction developable, based on undiscovered resource, is calculated in the same way used to determine the fraction discoverable: by considering cumulative investment in exploration. Similarly, the fraction recoverable uses cumulative investment in oil recovery to calculate the rate of progress in recovery technology, given that production is based and reduces the stock of identified reserve.

Fossil Fuel Production: United States and Global

Domestic natural gas and coal production, ROW fossil fuel production

Alaskan oil production, natural gas and coal production modules, both domestic and international, are built on the structure of the domestic oil production module. Development and exploration are formulated taking into account the stocks of undiscovered resource and identified reserves and energy prices. The production process accounts for recovery technology and considers production capacity and recoverable reserves, to determine the production rate. Exploration, Development, demand and production are here merged into a larger module, as shown below. Capital and technology are developed in separate modules.

Figure 18: Sketch of the ROW Production: Oil module



Fossil Fuel Production: Canada and Mexico

Purpose and Approach

The purpose of the Fossil Fuel Production module for Canada and Mexico is to calculate tar sands, oil, natural gas, and coal production and to keep track of both national fossil fuel resources and reserves. The approach used for modeling fossil fuel and non-fuels minerals resource in place is based upon the main groups of the McKelvey box (Figure 12), which divides them between undiscovered resources and identified reserves.

Explanation

Major Assumptions

- Fossil fuel resource is finite;
- Exploration and production, separately, determine the availability of recoverable resources for production;
- Oil prices influence the development of tar sands, a direct substitute for conventional liquid fuels;
- Technology affects the effectiveness of exploration and recovery activities.

Input Variables[12]

Variable Name	Module of Origin
Coal Fraction Discoverable	Production: Coal
Coal Fraction Recoverable	Production: Coal
Country Coal Demand	*Country* Energy Demand
Country Natural Gas Demand	*Country* Energy Demand
Country Oil Demand	*Country* Energy Demand
Natural Gas Fraction Discoverable	Production: Natural Gas
Natural Gas Fraction Recoverable	Production: Natural Gas
Oil Fraction Discoverable	Oil: Production Technology
Oil Fraction Recoverable	Oil: Production Technology
ROW Oil Price	ROW Resources Price and Cost: Oil

Output Variables

	Module of Destination		
Variable Name	**In the Same Sector**	**In Other Environmental Sectors**	**In Other Sectors**
Country Coal Production	*Country* Energy Trade		
Country Natural Gas Production	*Country* Energy Trade		
Country Oil Production	*Country* Energy Trade		
Country Tar Sands Production	*Country* Energy Trade		

[12] *Country* indicates Canada and Mexico, separately, for which the same structure has been customized for both countries.

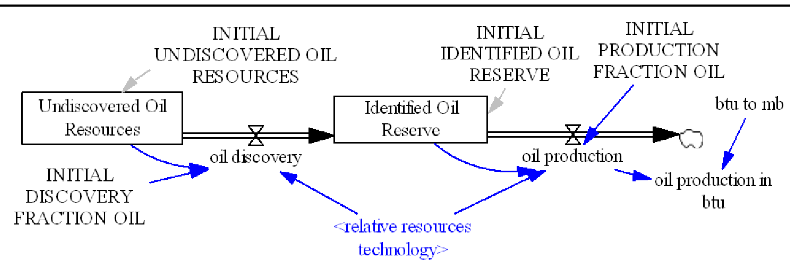
Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Country Initial Discovery Fraction Coal	Constant	Data on coal resources and production (EIA)
Country Initial Discovery Fraction Gas	Constant	Data on gas resources and production (EIA)
Country Initial Discovery Fraction Oil	Constant	Data on oil resources and production (EIA)
Country Initial Discovery Fraction Tar Sands	Constant	Data on tar sands resources and production (EIA)
Country Initial Identified Coal Reserve	Constant	Data on coal resource and reserve (EIA)
Country Initial Identified Gas Reserve	Constant	Data on gas resource and reserve (EIA)
Country Initial Identified Oil Reserve	Constant	Data on oil resource and reserve (EIA)
Country Initial Identified Tar Sands Reserve	Constant	Data on tar sands resource and reserve (EIA)
Country Initial Production Fraction Coal	Constant	Data on coal reserve and production (EIA)
Country Initial Production Fraction Gas	Constant	Data on gas reserve and production (EIA)
Country Initial Production Fraction Oil	Constant	Data on oil reserve and production (EIA)
Country Initial Production Fraction Tar Sands	Constant	Data on tar sands reserve and production (EIA)
Country Initial Undiscovered Coal Resources	Constant	Data on coal resources and reserve (EIA)
Country Initial Undiscovered Gas Resources	Constant	Data on gas resources and reserve (EIA)
Country Initial Undiscovered Oil Resources	Constant	Data on oil resources and reserve (EIA)
Country Initial Undiscovered Tar Sands Resources	Constant	Data on tar sands resources and reserve (EIA)

Functional Explanation

The recovery (production) of fossil fuels (tar sands, oil, gas, and coal) is modeled using the structure illustrated in Figure 19. Since the production of fossil fuels is identical for oil, natural gas, and coal, only oil production is explained in the following paragraphs. Tar sands production is proposed separately.

Figure 19: Structure of the Energy Supply Model for Fossil Fuels



Fossil Fuel Production

Exploration leads to discoveries, which gradually reduce the stock of *undiscovered resources*. The *identified reserve* is increased through discovery and decreased by production. The discovery rate is equal to *undiscovered resource* multiplied by *initial discovery fraction* times the relative fraction discoverable (technology improvement):

oil discovery[country]= MAX(0, initial discovery fraction oil[country]*Undiscovered Oil Resources[country]*relative oil fraction discoverable)

Similarly, the production rate is equal to *identified reserve* multiplied by *production fraction*, which is calculated as *initial production fraction*, multiplied by the *relative fraction recoverable* (technology improvement) and by *relative oil demand*, which represents increasing domestic needs of oil:

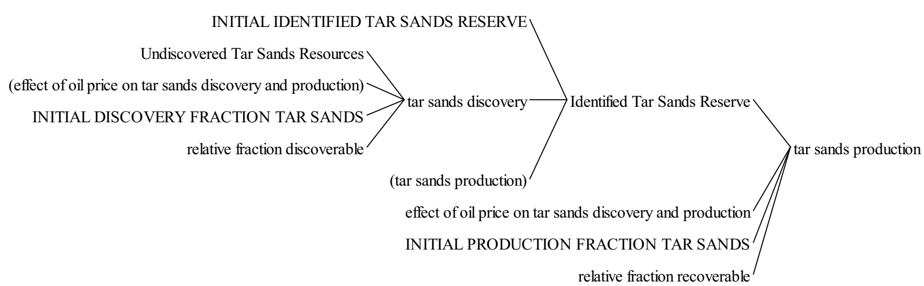
oil production[country]= Identified Oil Reserve[country]*production fraction oil[country]

production fraction oil[country]= INITIAL PRODUCTION FRACTION OIL[country]*relative oil fraction recoverable*relative oil demand[country]

The quantity of both *undiscovered resource* and *identified reserve* is related to technology. As a consequence of improvements in technology, resources and reserves may become recoverable or economically extractable, thus increasing the quantity available.

Tar Sands Production

Figure 20: Sketch of the main factors influencing Tar Sands Production



As in the case of oil and other fossil fuels, exploration leads to discoveries of tar sands, which gradually reduce the stock of *undiscovered resources*. The *identified reserve* is increased through discovery and decreased by production. Nevertheless, since tar sands production is constrained by the cost of extraction and refining, the differentiation between undiscovered and identified resource and reserves can also be seen as a way to distinguish between the part of the stock (total URR) that is economically recoverable and the one that is not. For this reason both discovery and recovery (production) are influences by oil prices in T21-NA.

The discovery rate is equal to *undiscovered resource* multiplied by *initial discovery fraction,* times technology improvement and the *effect of oil price on tar sands discovery and production*:

> tar sands discovery[country]= MAX(0, INITIAL DISCOVERY
> FRACTION TAR SANDS[country]* Undiscovered Tar Sands
> Resources[country]*relative oil fraction discoverable*Effect Of
> Oil Price On Tar Sands Discovery And Production)

Similarly, the production rate is equal to *identified reserves* multiplied by *initial production fraction,* times technology improvement and the *effect of oil price on tar sands discovery and production*:

> tar sands production[country]= MAX(0, Identified Tar Sands
> Reserve[country]* INITIAL PRODUCTION FRACTION TAR
> SANDS[country]*relative oil fraction recoverable□*Effect Of
> Oil Price On Tar Sands Discovery And Production)

It is assumed that the *effect of oil price on tar sands discovery and production* is mainly determined by world oil prices. The impact of prices on tar sands production is less than proportional (due to the fact that increasing energy prices increase the cost of production of tar sands, therefore increasing the economic threshold for economically sustainable production) and a delay is assumed to take place between the time oil prices increase and tar sands production output grows:

> Effect Of Oil Price On Tar Sands Discovery And Production=
> DELAY N(relative row oil price^0.35, 1, 1, 1)

Ethanol

Purpose and Approach

The purpose of the US Ethanol Production module is to calculate ethanol production and to keep track of bushels, land and water required, considering that USDA subsidies are allocated as planned until 2016. The Ethanol Production Module also calculates the gross and net contribution of ethanol to total gasoline consumption.

Explanation

Major Assumptions

- In order of priority: domestically grown corn is firstly consumed for domestic food production, then used for ethanol production and finally exported;
- Water used per bushel for growing corn is assumed to be constant;
- Total population and a constant value for per capita corn consumption define domestic corn consumption for food production;
- Total average water use per hectare of agriculture land is assumed to be constant for future projections;
- The energy return on investment for first generation corn ethanol is assumed to be equal to 20%.

Input Variables

Variable Name	Module of Origin
Agricultural Land in Use	US Land
Agriculture Production in Tons	US Agriculture Production
Harvested Area[corn]	US Agriculture Production
Motor Gasoline Consumption	US Energy Demand: Transportation Fleet
Total Population	US Population
Yield	US Agriculture Production

Output Variables

	Module of Destination		
Variable Name	**In the Same Sector**	**In Other Environmental Sectors**	**In Other Sectors**
Ethanol Production		Demand and Import: Synfuel and Biofuel	

Constants and Table functions

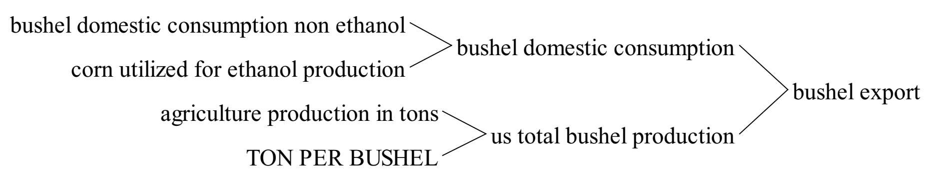
Variable Name	Type of Variable	Source for Estimation
Average water use per ha	Time Series	USDA
Corn to ethanol conversion	Constant	EIA
Ethanol EROI	Constant	Policy Variable
PC bushel domestic consumption non ethanol	Time Series	USDA
Ton to bushel conversion	Constant	USDA
Total renewable water	Constant	FAO
Water used per bushel	Constant	USDA

Functional Explanation

Ethanol production is influenced by a variety of factors. Direct inputs to production are land used and yield. Secondarily, calculated as indicators in the model, corn requires water and fertilizer, with the latter being excluded from this version of the model.

Corn bushels production and use

Figure 21: Sketch of the main factors influencing Corn Bushel Export



Corn production is calculated and obtained from the agriculture sector, using a Cobb-Douglas production function that uses land, capital, labor and total factor productivity, with the latter including the impact of energy prices. Total corn production is converted into bushels:

> us total bushel production =
> agriculture production in tons[MAIZE]/TON PER BUSHEL

Nationally produced corn can be used for domestic food and ethanol production, or it can be exported. Domestic consumption is calculated as the sum between corn used for food and ethanol production, with the former using the product of total population and per capita corn consumption:

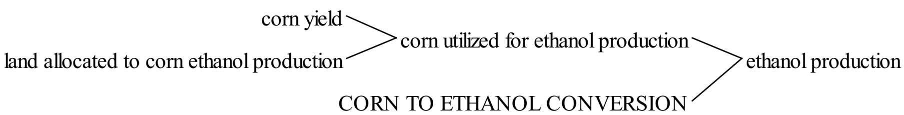
> bushel domestic consumption = bushel domestic consumption non ethanol + corn utilized for ethanol production
>
> bushel domestic consumption non ethanol= PC BUSHEL DOMESTIC CONSUMPTION NON ETHANOL(Time)*total population

Corn export is calculated as the difference between production and domestic consumption:

> bushel export= us total bushel production-bushel domestic consumption

Ethanol production

Figure 22: Sketch of the main factors influencing Ethanol Production



Once corn production is calculated, the factors influencing ethanol production are introduced. Land used for ethanol production is calculated using the minimum between total land cultivated with corn (both for ethanol and export), which is obtained by calculating the equivalent land needed for total US bushel production, and the land that should be made available to ethanol according to projections made available by USDA, which take into account the allocation of subsidies until 2016:

> land allocated to corn ethanol production = MAX(0, IF THEN ELSE (land allocated for ethanol>maximum land allocated to corn ethanol production, maximum land allocated to corn ethanol production, land allocated for ethanol))
>
> maximum land allocated to corn ethanol production= (us total bushel production-bushel domestic consumption non ethanol)/corn yield

Knowing the amount of land allocated to corn for ethanol production and the average yield of each hectare in bushels, allows calculating the total amount of bushels that is actually harvested for ethanol production. This value is then converted into gallons using a constant conversion factor.

> corn utilized for ethanol production= land allocated to corn ethanol production*corn yield
>
> ethanol production= corn utilized for ethanol production*ETHANOL TO CORN PRODUCTION

Estimating the impacts of ethanol production

Various indicators are calculated to understand what the impact of ethanol production may be. Assuming the allocation of subsidies until 2016 and production growth, endogenously calculated, similar to what projected by USDA, the impact of ethanol production are estimated for land use, water use and contribution to motor gasoline consumption.

Land use for corn ethanol is compared both with total corn cultivated area and agricultural area:

> percentage of corn for ethanol land over total corn land= land
> allocated to corn ethanol production/harvested area[MAIZE]
>
> percentage of corn for ethanol land over total agricultural land= land
> allocated to corn ethanol production/agricultural land in use

Water use for corn ethanol production is compared to water use in the agriculture sector and to total US renewable water.

> water used for corn ethanol production=
> corn utilized for ethanol production*WATER USED PER BUSHEL
>
> fraction of agriculture water for ethanol=
> water used for corn ethanol production/total agriculture water use
>
> fraction of renewable water for ethanol=
> water used for corn ethanol production/TOTAL RENEWABLE WATER

The impact of domestic ethanol production on the transportation sector proposed in the present study consist in comparing the gross and net contribution of ethanol to the transportation sector, more specifically to motor gasoline consumption. The net contribution is calculated using a constant value for the energy return on investment, which is set to 20% in the base case.

> percentage of motor gasoline demand from ethanol=
> ethanol production/motor gasoline consumption
>
> percentage of net ethanol energy gain over motor gasoline demand=
> net energy gain/motor gasoline consumption

Electricity

Purpose and Approach

The Electricity Fuel Demand module represents the demand of non-renewable energy sources necessary to generate electricity. Demand of oil, natural gas, coal and nuclear energy for electricity production are represented and calculated endogenously.

Explanation

Major Assumptions

- Non-renewable energy sources demand for electricity production is influenced by three factors:
    - the efficiency in generating electricity;
    - the effect of the resource price with respect to electricity price;
    - the effect of the energy source price on demand for production.
- All the electricity demanded from renewable resources is assumed to be generated from renewable sources of energy.

Input Variables

Variable Name	Module of Origin
Coal Price Substitutability	Energy Prices
Effect of coal price on energy demand	Effect of Price on Demand
Effect of natural gas price on energy demand	Effect of Price on Demand
Effect of oil price on energy demand	Effect of Price on Demand
Electricity Price Substitutability	Energy Prices
Natural Gas Price Substitutability	Energy Prices
Nuclear electricity generation in BKWH	Demand and Import: Nuclear Energy
Nuclear Price Substitutability	Energy Prices
Oil Price Substitutability	Energy Prices
QDBTU to BKWH	Demand and Import: Electricity
Total fossil fuel electricity demand in BKWH	Demand and Import: Electricity

Output Variables

Variable Name	Module of Destination		
	In the Same Sector	In Other Energy Sectors	In Other Sectors
Coal electricity generation in BKWH	Production: Electricity Generation by Fuel		
Electricity coal demand in QDBTU		Demand and Import	
Electricity nuclear Demand in QDBTU		Demand and Import	
Electricity oil demand in QDBTU		Demand and Import	
Gas electricity generation in BKWH	Production: Electricity Generation by Fuel		
Gas electricity generation in BKWH	Production: Electricity Generation by Fuel		
Oil electricity generation in BKWH	Production: Electricity Generation by Fuel		

Constants and Table functions

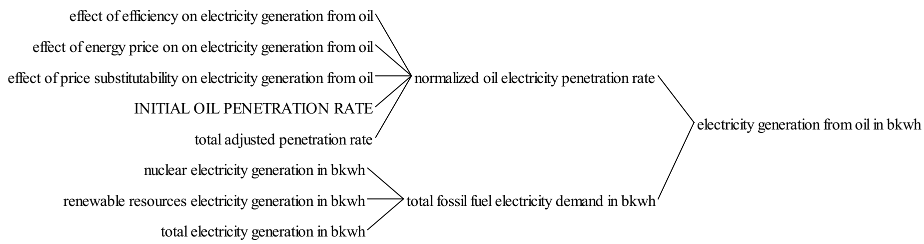
Variable Name	Type of Variable	Source for Estimation
Coal generation efficiency table	Time series	EIA
Elasticity of coal electricity generation to shock price	Constant	Estimated
Elasticity of coal penetration to profitability	Constant	Estimated
Elasticity of efficiency on coal electricity generation	Constant	Estimated
Elasticity of efficiency on natural gas electricity generation	Constant	Estimated
Elasticity of efficiency on nuclear electricity generation	Constant	Estimated
Elasticity of efficiency on oil electricity generation	Constant	Estimated
Elasticity of natural gas electricity generation to shock price	Constant	Estimated
Elasticity of natural gas penetration to profitability	Constant	Estimated
Elasticity of nuclear electricity generation to shock price	Constant	Estimated
Elasticity of nuclear penetration to profitability	Constant	Estimated
Elasticity of oil electricity generation to shock price	Constant	Estimated
Elasticity of oil penetration to profitability	Constant	Estimated
Gas generation efficiency table	Time series	EIA
Initial coal generation efficiency	Constant	EIA
Initial coal penetration Rate	Constant	EIA
Initial gas generation efficiency	Constant	EIA
Initial natural gas penetration rate	Constant	EIA
Initial nuclear generation efficiency	Constant	EIA
Initial nuclear penetration rate	Constant	EIA
Initial oil generation efficiency	Constant	EIA
Initial oil penetration rate	Constant	EIA
Nuclear generation efficiency able	Time series	EIA
Oil generation efficiency table	Time series	EIA

Functional Explanation

Since fossil fuel demand for electricity production is represented in the same way for oil, natural gas and coal, only the structure created for oil demand will be presented. Nuclear energy demand for electricity production is assumed to be equal to nuclear electricity generation (which is a policy variable).

Oil demand for electricity production

Figure 23: Sketch of the main factors influencing Electricity Generation from Oil



The demand of oil for electricity production is calculated by multiplying the total fossil fuel demand for electricity production by the penetration rate of oil in electricity production:

> *oil electricity generation in bkwh = (normalized oil electricity penetration rate*total fossil fuel electricity demand in bkwh)*

Total Fossil Fuel Electricity Demand in BKWH is calculated as the *Total Electricity Generation in BKWH* minus renewable resources and nuclear electricity generation in BKWH:

> total fossil fuel electricity demand in bkwh= total electricity generation in bkwh-renewable resources electricity generation in bkwh-nuclear electricity generation in bkwh

The variable *Normalized Oil Electricity Penetration Rate* is equal to its indicated value divided by the total adjusted penetration rate for the three fossil fuels:

> normalized oil electricity penetration rate= oil electricity indicated penetration rate/total adjusted penetration rate

The indicated penetration rate of oil in electricity production is calculated by taking into consideration the Initial Oil Penetration Rate and the effect of oil price, of oil price with respect to electricity price, and efficiency, on electricity production by utilizing oil:

> oil electricity indicated penetration rate= INITIAL OIL PENETRATION RATE*effect of efficiency on oil electricity production/effect of price substitutability on oil electricity production/effect of energy price on oil electricity production

The *Effect of Energy Price on Oil Electricity Production* is equal to:

effect of energy price on oil electricity production= Effect Of Oil Price On Energy Demand^ELASTICITY OF OIL ELECTRICITY GENERATION TO SHOCK PRICE

Similarly, the *Effect of Price Substitutability on Oil Electricity Production* is calculated as *Relative Oil Price Substitutability* (which is equal to *Oil Price Substitutability* over *Electricity Price Substitutability*) to the power of the *Elasticity of Oil Penetration to Profitability*:

effect of price substitutability on oil electricity production= Relative Oil Price Substitutability^ELASTICITY OF OIL PENETRATION TO PROFITABILITY

The *Effect of Efficiency on Oil Electricity Production* is calculated once again as *Relative Oil Generation Efficiency* to the power of *Elasticity of Efficiency on oil Electricity Generation*. The oil efficiency in generating electricity is exogenously calculated and a projection is made for the future years.

effect of efficiency on oil electricity production= relative oil generation efficiency^ELASTICITY OF EFFICIENCY ON OIL ELECTRICITY GENERATION

relative oil generation efficiency= oil electricity generation efficiency/INITIAL OIL GENERATION EFFICIENCY

Energy Sources Electricity Penetration Rate

The penetration rate of each energy source utilized to produce electricity is calculated as the electricity generation from a specific source (in BKWH) over the *Total Electricity Generation in BKWH*:

renewable resources electricity penetration rate= renewable resources electricity generation in bkwh/total electricity generation in bkwh

nuclear electricity penetration rate= nuclear electricity generation in bkwh/total electricity generation in bkwh

Fossil Fuel Electricity Penetration Rate is calculated as the sum of natural gas, oil and coal penetration rate for electricity production:

fossil fuels electricity penetration rate= coal electricity penetration rate+natural gas electricity penetration rate+oil electricity penetration rate

Energy Return on Investment EROI

Purpose and Approach

The purpose of the Energy Return on Investment EROI module is to calculate the energy return on investment of fossil fuels in the U.S. Energy input to production and energy output (fossil fuels) are calculated to analyze the impact of depletion and energy prices on fossil fuel production in the U.S., which has reached its peak in oil and natural gas production.

Explanation

Major Assumptions

- Two different methods are used to calculate the energy return on investment for oil and gas;
- Method I: Energy Input is calculated as the summation of Direct and Indirect Energy inputs. Direct Energy inputs refer to the fuels used in the mining and production process, while the Indirect Energy inputs refers to the investments into capital to produce the energy.
- Method I: Indirect energy inputs for oil and gas is a function of oil and gas investment, based on expected demand, market profitability, and resource availability, converted to an energy value (Energy Intensity). Direct energy Inputs are calculated as a function of oil and gas depletion (i.e. it will take proportionally more energy to extract the remaining ones).
- Method II: uses the same basic energy output over input formula, but derives the inputs in a novel way. The energy inputs are initialized by the share of the energy outputs in 1980, and are then driven by depletion.

Input Variables

Variable Name	Module of Origin
Alaska Oil Discovered Reserves	US Production: Oil Alaska
Alaska Oil Undiscovered Resources	US Production: Oil Alaska
Alaska total oil in place	US Production: Oil Alaska
Coal Investment	US Energy Investment
Coal Production in Qdbtu	US Total Energy Production
GDP deflator	US Households Account
Gross national product	US Balance of Payments
Industry production	US Industry Production
Natural Gas Discovered Reserves	US Production: Natural Gas
Natural Gas Production in Qdbtu	US Total Energy Production
Natural Gas Total Resource	US Production: Natural Gas
Natural Gas Undiscovered Resources	US Production: Natural Gas
Normalized industrial electricity net demand	US Energy Demand: Industrial
Oil and gas investment	US Energy Investment
Oil Production in Qdbtu	US Total Energy Production
Oil Proved Reserve	US Production: Oil

Oil Total Resource	US Production: Oil
Oil Unproved Resource	US Production: Oil
Total electricity demand in Qdbtu	US Demand and Import: Electricity
Total indicated sectoral energy demand	US Total Energy Demand
Total Industrial Indicated Energy Demand	US Energy Demand: Industrial
US total energy demand in Qdbtu	US Total Energy Demand

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Initial direct energy input	Constant	Economic Census
Initial share of energy input over output	Constant	Economic Census

Functional Explanation

The energy return on investment (EROI)**,** a concept born from physics (Hall et al., 1986), is the energy returned from an activity compared to the energy invested in that process (Cleveland and Kaufmann, 2001). The basic equation is:

$$EROI = \frac{\text{Energy gained from an activity}}{\text{Energy used in that activity}}$$

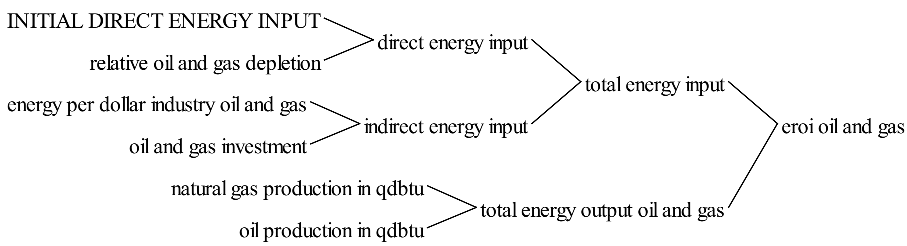
EROI represents the ability of energy to do useful work, quantifying the amount of energy available to do work by creating a ratio that represents the amount of energy that a body has to do work relative to the amount of energy it produces. This means that if the EROI of a theoretical economy's fuel source is 20:1 for every 100 units of energy brought into that economy 5 had to be invested to produce that 100. Therefore, the net amount of energy available for other productive uses is not 100 units, but rather 95 units. EROI takes into account the concept of net energy and the ability of a fuel source to produce surplus energy, which allows society and the economy to exist and grow (Hall et al., 1986; Cleveland et al., 1984).

EROI should not be confused with conversion efficiency, which is the efficiency with which one fuel is transformed or upgraded to another. However, losses associated with these transformations are included in the EROI calculation. Finally, the denominator for EROI is usually calculated from the perspective of energy that is already delivered, or readily deliverable, to society that is then used to get the new energy. This is what differentiates EROI from exergy (Odum, 1983), which also looks at the work done by biological systems. For example, accessing new oil reserves may require energy used previously in a steel mill to make pipes or bits, and hence that is energy that has already been delivered to society. Likewise oil is usually pumped from the ground by burning natural gas to generate electricity to run pumps. That gas (or the electricity) can usually be transferred to the rest of society very readily, but has instead been diverted to get the oil. So we would consider both of these costs as existing energy that has been diverted from society and include them in the EROI calculation.

T21-NA calculates EROI in two different ways: a conventional one (Cleveland, 2005; Cleveland, 1992) with investments and outputs defining the energy gain, and second one in which energy inputs are a function of energy output and depletion.

Oil and Gas EROI: Method I

Figure 24: Sketch of the main factors influencing EROI Oil and Gas, Method I



The first method used by T21-NA to calculate the Energy Return on Investment (EROI) for petroleum (oil and gas) and coal is similar to the methods used by Cleveland (Cleveland and Kaufmann, 2001; Cleveland, 1992). In this method we calculate Energy Input as the summation of Direct and Indirect Energy inputs. Direct Energy inputs refer to the fuels used in the mining and production process, while the Indirect Energy inputs refers to the investments into capital to produce the energy.

eroi oil and gas1= total energy output oil and gas/total energy input

total energy output oil and gas=
oil production in qdbtu+natural gas production in qdbtu

total energy input = direct energy input + indirect energy input

The EROI for oil and gas is given as a single value since the majority of oil and gas are found together in the same fields (Cleveland and Kaufmann, 2001). Indirect energy inputs for oil and gas is a function of oil and gas investment as calculated by T21, based on expected demand, market profitability, and resource availability, converted to an energy value (Energy Intensity). Direct energy Inputs are calculated as a function of oil and gas depletion. The assumption here is that as more resources are used, it will take proportionally more energy to extract the remaining ones.

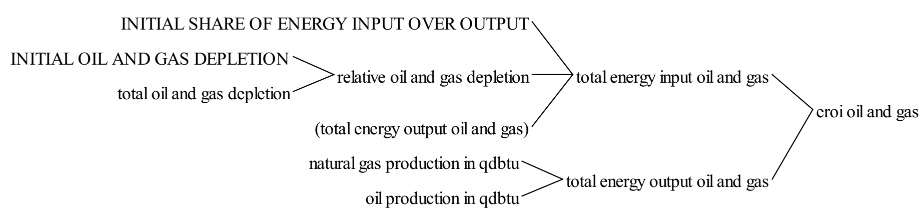
direct energy input=
INITIAL DIRECT ENERGY INPUT/relative oil and gas depletion

indirect energy input=
energy per dollar industry oil and gas*oil and gas investment

energy per dollar industry oil and gas=
total industrial indicated energy demand/real gross national product

Oil and Gas EROI: Method II

Figure 25: Sketch of the main factors influencing EROI Oil and Gas, Method II



The second method used in the model to calculate EROI for petroleum still uses the same basic energy output over input formula, but derives the inputs in a novel way. The energy inputs are initialized by the share of the energy outputs in 1980, and are then driven by depletion.

total energy input II= total energy output oil and gas*INITIAL SHARE OF ENERGY INPUT OVER OUTPUT/relative oil and gas depletion

This assumption has been made because as oil and gas become more and more depleted, it will take more and more energy to find and bring them to the surface, but still the effort for oil and gas production is anchored to demand and therefore production, through prices. In other words, at the beginning of production, technology and investment are the major determinants of the production rate, but as time progresses depletion becomes the dominant factor.

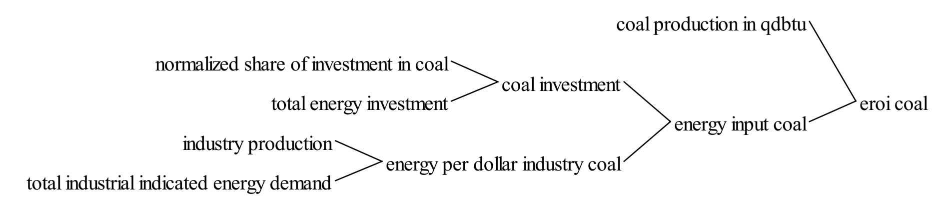
total oil and gas depletion=
(((Natural Gas Discovered Reserves+Natural Gas Undiscovered Resources)/QDBTU TO BCF)+((Oil Proved Reserve+Oil Unproved Resource+Alaska Oil Discovered Reserves+Alaska Oil Undiscovered Resources)/QDBTU TO MB(Time)))/

((OIL TOTAL RESOURCE+alaska total oil in place)/QDBTU
TO MB(Time)+natural gas total resource/QDBTU TO BCF)

The major exogenous factor used is the initial share of energy input over output which was derived empirically from the Economic Census data and Cleveland's studies (Cleveland, 1992; Cleveland and Kaufmann, 2001). This method assumes a theoretical EROI curve highly dependent on the amount of resources in the ground. At first, when only a small percentage of the fuel has been produced there is a very high EROI, because the high reservoir pressure allows oil and gas to reach the surface and be produced with very little additional energy investment. Then as more and more of the fuel is produced the reservoir pressure drops off and the rate of production eventually declines, unless technology (e.g. secondary and tertiary recovery), which requires additional energy input, are used.
Because U.S. production peaked 10 years before our model begins, the main driver of EROI for domestic oil is depletion, which is precisely why we use it to determine the energy inputs of oil and gas production.

Coal EROI

Figure 26: Sketch of the main factors influencing EROI for Coal



The only differences in the above method for coal is that we do not disaggregate direct and indirect energy inputs, and we used an energy per dollar conversion factor that uses industrial demand and production only.

eroi coal= coal production in qdbtu/energy input coal

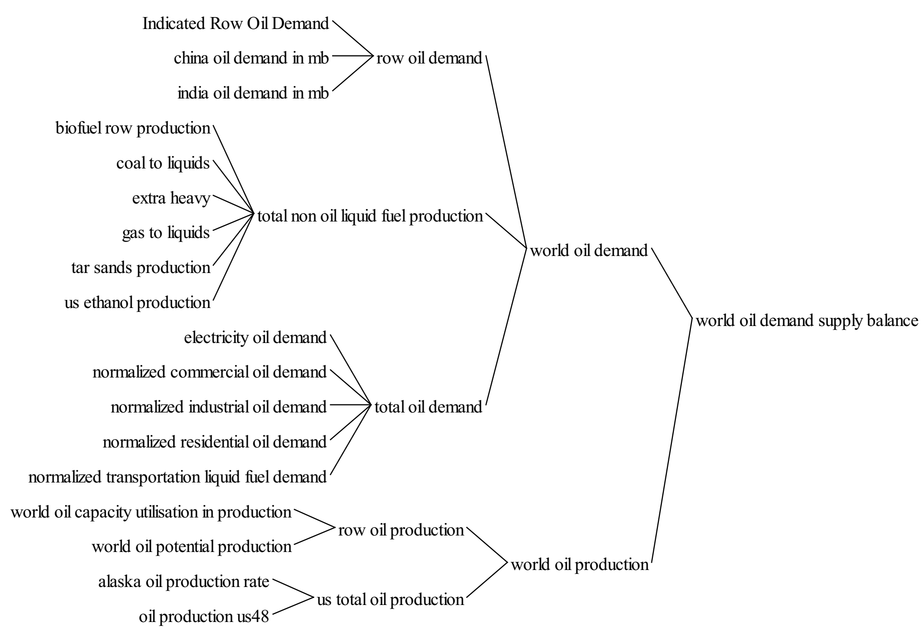
energy input coal= energy per dollar industry coal*coal investment

energy per dollar industry coal=
total industrial indicated energy demand/industry production

The only reason for using a different energy conversion factor is that recent research on coal EROI by ESF has used the formulation above, and the authors decided to follow the same method to ensure full compatibility and replicability of the results. We did not disaggregate the energy inputs into coal mining because domestically produced coal has not yet peaked and is not projected to peak (in quantity terms) until after the run of this model. This means that the energy it takes to find the coal and mine it is not projected to undergo any significant changes, and it makes sense to make the assumption that the direct energy inputs will always be half of the indirect energy inputs because this is what we have empirically observed in the U.S. economic census data (Economic Census, various years).

Total Demand, Supply, and Trade

Figure 27: Sketch of the main factors influencing World Oil Demand and Supply Balance



Purpose and Approach

The purpose of the Energy Demand and Import module is to calculate total energy demand (disaggregated into oil, natural gas and coal), at both national and world level (disaggregated into China, India and rest of the world), and to compare it with domestic and international supply.

The main outputs of the Energy Demand and Import modules are import of fossil fuels and national and international demand supply balance.

In the case of oil, here presented, the Demand and Import module includes also demand for the Lower 48 States, desired and effective import (the latter takes into account the eventual shortage of oil and a consequent reduction of import for the U.S.)

Explanation

Major Assumptions

- Oil demand from the rest of the world is influenced only by oil price;
- The U.S. oil import is affected by the availability of oil in the world market. The bargaining power of the U.S. is assumed to be equal to the market share represented by its consumption;
- Indicated oil import is determined by potential domestic production and price.

Input Variables

Variable Name	Module of Origin
Alaska oil production rate	Production: Oil Alaska
China oil demand in Mb	ROW Energy Demand: China
Electricity oil demand in QDBTU	Production: Electricity Fuel Demand
India oil demand in Mb	ROW Energy Demand: India
Normalized commercial oil demand	Energy Demand: Commercial
Normalized industrial oil demand	Energy Demand: Industrial
Normalized residential oil demand	Energy Demand: Residential
Normalized transportation oil demand	Energy Demand: Transportation
Oil Production in Mb	Production: Oil
Potential US oil production	Production: US Oil Trend
Reference relative international oil price	ROW Energy Demand: China
Relative international oil price	ROW Energy Demand: China
World oil production rate	ROW Production: Oil

Output Variables

	Module of Destination		
Variable Name	**In the Same Sector**	**In Other Energy Sectors**	**In Other Sectors**
Effective US oil import		U.S. Fossil fuel emissions	
Oil dependency factor		Effect of Price on Demand	
Oil Demand for US48 Production		Production: Oil	
QDBTU to MB		U.S. Fossil fuel emissions, Production: Oil	
Total oil demand in MB		Resources Price and Cost: Oil, U.S. Fossil fuel emissions, Production: Oil	
US oil demand supply balance		Resources Price and Cost: Oil	
US Total Oil Production		ROW Resources Price and Cost: Oil	
World oil demand		ROW Resources Price and Cost: Oil	
World oil demand supply balance		ROW Oil Production	
World oil production		ROW Fossil fuel emissions, ROW Resources Price and Cost	

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Elasticity of oil import to price	Constant	Data on energy price and import (EIA)
Elasticity of oil price to ROW oil demand	Constant	Data on energy price and demand (EIA)
Initial oil import	Constant	EIA
ROW oil demand function	Time series	EIA

Functional Explanation

U.S. Oil Demand and Production

The variable *Total Oil Demand in MB* (million barrels) is calculated by summing oil demand from the residential, commercial, industrial, and transportation sectors and oil demand for electricity generation:

> total oil demand in mb = (electricity oil demand in qdbtu+normalized commercial oil demand+normalized industrial oil demand+ normalized residential oil demand+normalized transportation oil demand)*QDBTU TO MB(Time)

U.S. Total Oil Production is calculated as the sum of oil production in the US 48 and Alaska:

> us total oil production= alaska oil production rate+oil production in mb

Oil import is calculated for the US 48 and for the whole Nation. In the latter case two different formulations are utilized: the first one considers an unlimited international production, while the second takes into account an eventual shortage of oil in the world market.

> us 48 oil import= natural oil demand in us48-oil production in mb
>
> us oil imports in mb= total oil demand in mb - us total oil production
>
> effective us oil import= IF THEN ELSE(Time<2005, MIN(us 48 oil import,world oil production),MIN(us 48 oil import,world oil production*us share of oil world demand))

World Oil Demand and Production

The variable *World Oil Demand* is calculated as the sum of US, China, India and rest of the world fuel demand, minus the production of non conventional liquid fuels:

world oil demand=
(row oil demand+ US oil demand)-total non oil liquid fuel production

row oil demand=
indicated row oil demand + India oil demand in mb + China oil demand in mb

total non oil liquid fuel production=
us ethanol production + biofuel row production+tar sands production+coal to liquids+extra heavy oil+gas to liquids

While China and India oil demand are endogenously calculated (in the ROW Energy Demand sector), ROW oil demand is partially exogenous. It is equal to historical rest of the world oil demand, multiplied by the effect of oil price on the ROW demand itself.

The *Effect of Oil Price on ROW Oil Demand* is calculated as *Relative International Oil Price* over *Reference Relative International Oil Price* to the power of the *Elasticity of Oil Price to ROW Oil Demand*:

effect of oil price on row oil demand = IF THEN ELSE(Time<2005,1,(relative international oil price/REFERENCE RELATIVE INTERNATIONAL OIL PRICE)^ELASTICITY OF OIL PRICE TO ROW OIL DEMAND)

The IF THEN ELSE function is used to introduce the effect of oil price on ROW demand in 2005, at present time, given that historical data are used to compute *Indicated ROW Oil Demand*.

The variable *World Oil Production* is equal to the sum of U.S. and rest of the world oil production:

world oil production= world oil production rate + us total oil production

Total energy demand and supply

U.S. total energy demand is calculated as the sum of nuclear energy, renewable resources, coal, natural gas and oil demand:

us total energy demand in qdbtu=nuclear production in qdbtu+renewable resources production in qdbtu+total coal demand in qdbtu+total natural gas demand in qdbtu+total oil demand in qdbtu

Total energy supply is equal to the sum of domestic production and imports of oil and natural gas:

> total energy supply=total energy production+net natural gas imports in bcf/QDBTU TO BCF+effective us oil import/QDBTU TO MB(Time)

In addition, both domestic and total energy demand supply balance are calculated, as well as the medium term trend of domestic energy demand and the share of total demand of each energy source.

Energy Price and Cost

Purpose and Approach

The purpose of the Price and Cost module is to calculate domestic fossil price and production cost. Both values are calculated over the medium to longer term, making so that speculation and short term fluctuations are not taken into consideration. The main factors affecting fossil fuel price and cost are the availability of domestic reserve and resource, demand supply balance at both national and international level (both oil and liquid fuels are considered when calculating oil price and cost).
Modules focusing on oil are here presented, the calculation of natural gas and coal is based on the same structural assumptions.

Explanation

Major Assumptions

- Real oil price is influenced by availability of reserves, national and international demand supply balance;
- Real oil cost is influenced by the availability of reserves, national and international demand supply balance and the ratio recoverable reserves over demand.

Energy Prices

Input Variables

Variable Name	Module of Origin
Effective world oil recoverable reserves	ROW Production: Oil
GDP deflator	Relative Prices
ROW oil actual reserves production ratio	ROW Production: Oil
World fuel demand supply balance	Demand and Import: Oil
World oil demand	Demand and Import: Oil
World oil demand supply balance	Demand and Import: Oil
World Oil Potential Production	ROW Production: Oil

Output Variables

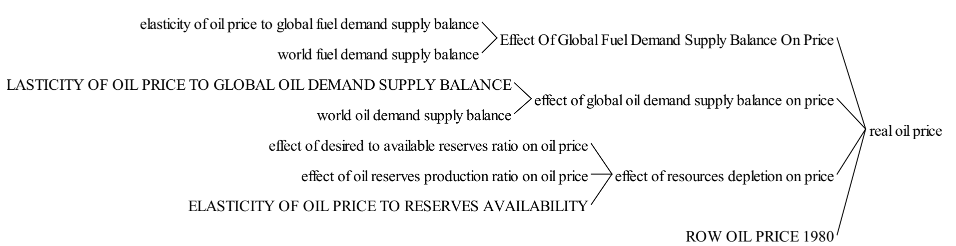
Variable Name	Module of Destination: In the Same Sector	In Other Energy Sectors	In Other Sectors
Real Oil Price		US Effect of Price on Demand; US Production: Oil Alaska	
Real ROW oil price per MBTU		ROW Energy Demand: China; ROW Energy Demand: India; US Effect of Price on Demand; Energy Prices; US Energy Expenditure	
Relative ROW oil price		Country Energy Demand; Country Energy Production; US Effect of Price on Demand	
ROW available production years	ROW Resources Price and Cost: Oil		
ROW demand supply balance		ROW Production: Oil	
ROW oil price per MBTU		ROW Production: Oil	

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Elasticity of oil price to ROW oil actual reserves production ratio	Constant	Estimated
Reference reserve production ratio	Constant	Estimated
ROW elasticity of oil price to demand supply balance	Constant	Estimated
ROW initial trend demand	Constant	EIA
ROW oil price 1980	Constant	EIA
ROW oil price 1980 BTU	Constant	EIA

Functional Explanation

Figure 28: Sketch of the main factors influencing Real Oil Price



The *Real Oil Price* is determined by the interaction of the following elements: initial oil price, oil and fuel domestic and international demand supply balance, and the effect of depletion:

> real oil price= ROW OIL PRICE 1980*effect of oil resources availability on world price*Effect Of World Fuel Demand Supply Balance On Price*row effect of oil demand supply balance on price

Effect of availability of reserves on oil price

The variable *Effect of Oil Resources Availability on World Price* represents the effect of the ratio actual and desired recoverable reserve remaining (longer term effect) as well as the impact of the reserve production ratio (medium term effect).

The value of the desired recoverable reserves is calculated by considering oil demand, an adjustment based on demand growth (trend function), and a second adjustment based on the reserve production ratio (to take into account the sustainability of production):

> row desired recoverable oil = world oil demand+row adjustment of total recoverable resources remaining+row adjustment for expected growth in demand

Energy Production Costs

Input Variables

Variable Name	Module of Origin
Effective world oil recoverable reserves	ROW Production: Oil
GDP deflator	Relative Prices
ROW available production years	ROW Resources Price and Cost: Oil
World fuel demand supply balance	Demand and Import: Oil
World oil demand	Demand and Import: Oil
World oil demand supply balance	Demand and Import: Oil
ROW oil price per MBTU	ROW Resources Price and Cost: Oil
Real ROW oil price per MBTU	ROW Resources Price and Cost: Oil

Output Variables

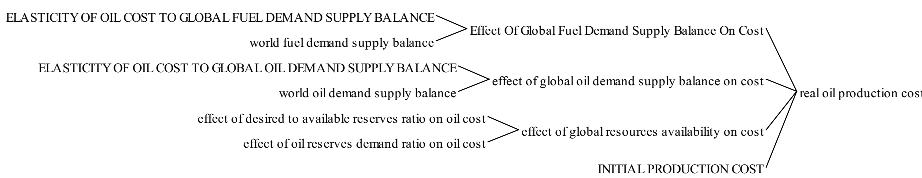
	Module of Destination		
Variable Name	In the Same Sector	In Other Energy Sectors	In Other Sectors
World oil production cost		ROW Production: Oil	
World real oil price over cost		Energy Markup	

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Elasticity of oil cost to demand supply ratio	Constant	Estimated
Elasticity of oil cost to world recoverable reserve demand ratio	Constant	Estimated
World oil production cost 1980	Constant	EIA

Functional Explanation

Figure 29: Sketch of the main factors influencing Real Oil Production Cost



Real Oil Production Cost is determined by the interaction of the following elements: initial oil cost, domestic and international oil and liquid fuel demand supply balance, and the availability of reserves and resources:

> real oil production cost = INITIAL WORLD OIL PRODUCTION COST*world effect of resources on cost*Effect Of World Fuel Demand Supply Balance On Row Cost*row effect of oil demand supply balance on row cost

Demand and supply balance for oil and liquid fuel are calculated in the same way as for the calculation of oil price. What differs, is the effect of resources availability (depletion) on cost. In this case, only the ratio actual to desired recoverable reserves is used, to represent the longer term implication of depletion on production cost, excluding the medium term impact of the reserve to production ratio (which is more likely to create speculation for oil price and little longer term impacts, especially after peak oil has taken place).

Effect of availability of recoverable reserves on oil price

The variable *Oil Desired Available Ratio Effect on Cost*, used to calculate the effect of oil resources availability on production cost, represents the number of years in which the actual demand can be guaranteed by actual recoverable resource remaining.

The relative value of this variable, calculated as the ratio between recoverable reserve remaining and desired recoverable oil (which is determined primarily using oil demand), is used to calculate the *oil production cost*:

> row available production years= effective world oil recoverable reserves/row desired recoverable oil

Energy Investment, Capital and Technology

Energy Investment

Purpose and Approach

The Energy Investment module represents the allocation of investment in the energy sector for each energy source (oil, natural gas, coal and renewable resources).

Explanation

Major Assumptions

- Allocation of investment to a specific energy source depends on its specific margin;
- Investment in the energy market is based on actual production, average profitability of the market and technology.

Input Variables

Variable Name	Module of Origin
Investment industry	Investment
Real Coal price over cost	Energy Markup
Real GDP at market prices	Investment
Real natural gas price over cost	Energy Markup
Real Oil price over cost	Energy Markup
Real Uranium price over cost	Energy Markup
Relative average energy markup	Energy Markup
Relative energy production	Energy Markup
Relative resources technology	Technology
Renewable resources margin	Energy Markup

Output Variables

	Module of Destination		
Variable Name	In the Same Sector	In Other Energy Sectors	In Other Sectors
Coal Investment		Energy Resources Capital and Technology	
Natural Gas Investment		Energy Resources Capital and Technology	
Nuclear investment		Energy Resources Capital and Technology	
Oil Investment		Energy Investment: Oil	
Renewable Resources investment		Energy Resources Capital and Technology	

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Elasticity of Energy Investment to Technology	Constant	Estimated
Elasticity of investment in coal to markup	Constant	Estimated
Elasticity of investment in gas to markup	Constant	Estimated

Elasticity of investment in nuclear to markup	Constant	Estimated
Elasticity of investment in renewable resources to markup	Constant	Estimated
Elasticity of Investment to Energy Production	Constant	Estimated
Elasticity of investment to energy sector to markup	Constant	Estimated
Energy Investment Delay Time	Constant	Estimated
Initial share of GDP invested in energy sector	Constant	EIA, BEA
Initial share of investment for coal	Constant	Estimated
Initial share of investment for natural gas	Constant	Estimated
Initial share of investment for nuclear	Constant	Estimated
Initial share of investment for Oil	Constant	Estimated
Initial share of investment for renewable resources	Constant	Estimated

Functional Explanation

The Energy Investment module calculates both *Total Energy Investment* in the energy market and the allocation of the investment to each energy source.

Total Energy Investment

The Total Energy Investment is calculated by multiplying the Share of GDP Invested in Energy Sector by the Real GDP at Market Prices:

> total energy investment= real gdp at market prices*Share Of Gdp
> Invested In Energy Sector

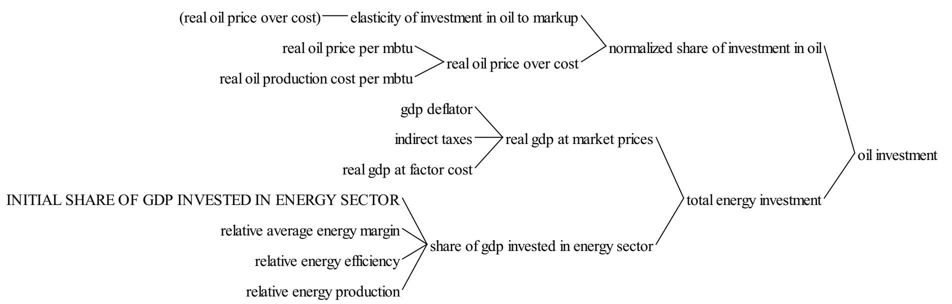
The Share of GDP invested in Energy Sector is a delayed function of its indicated value. A delay of one year is considered to take into account the time necessary to collect data and perceive information.

The *Indicated Share of GDP Invested in Energy Sector* is based on its initial value (in 1980), relative energy production (to account for the short term energy needs), average profitability of the energy market (to include the likely availability of funds for investments in energy with respect to other economic sectors) and technology (to represent the declining energy intensity of GDP and declining relative needs for energy):

> indicated share of gdp invested in energy sector=
> ((INITIAL SHARE OF GDP INVESTED IN ENERGY
> SECTOR*
> relative energy production^ELASTICITY OF INVESTMENT TO
> ENERGY PRODUCTION)*relative average energy
> margin^ELASTICITY OF INVESTMENT TO ENERGY
> SECTOR TO MARKUP)/relative energy
> efficiency^ELASTICITY OF ENERGY INVESTMENT TO
> TECHNOLOGY

Oil and Energy Investment

Figure 30: Sketch of the main factors influencing Oil Investment



Oil, and more in general energy investment (natural gas, coal and renewable energy), is calculated by multiplying the Share of *Total Energy Investment* by the normalized share for oil:

> oil investment= normalized share of investment in oil*total energy investment

The share invested in the oil sector is a delayed function of its indicated value and normalized to make sure 100% of the available total energy investment is consistently allocated. A delay of one year is considered to take into account the time necessary to collect data and perceive information to then allocate investment across different energy sources.

The *Indicated Share of Investment for Oil* is based on its initial value (in 1980) and the relative oil margin (price over cost), which in turns depends on the availability of resource and reserves. Since investment cannot be negative, a MAX function is used (depreciation is accounted for in the *Energy Capital* sector).

> indicated share of investment for oil=MAX(INITIAL SHARE OF INVESTMENT FOR OIL*relative oil price over cost^elasticity of investment in oil to markup,0)

Energy Capital

Purpose and Approach

The Energy Capital module represents the stock of capital available per each energy source (coal, renewable, natural gas and nuclear) that is used to calculate production capacity. Investment is the main input and stock of capital and depreciation are represented.

Explanation

Major Assumptions

- Both a construction delay and an average capital lifetime are used to represent the availability of efficient capital (which is converted into infrastructure).

Input Variables

Variable Name	Module of Origin
Coal Investment	Energy Investment
Nuclear investment	Energy Investment
Natural Gas Investment	Energy Investment
Renewable Resources investment	Energy Investment

Output Variables

	Module of Destination		
Variable Name	In the Same Sector	In Other Energy Sectors	In Other Sectors
Coal Capital		Energy Technology, Production: Coal	
Coal capital discard rate		Energy Technology	
Coal Investment rate		Energy Technology	
Natural Gas Capital		Energy Technology, Production: Natural Gas	
Natural Gas capital discard rate		Energy Technology	
Natural Gas Investment rate		Energy Technology	
Renewable Resources Capital		Production: Renewable Resources	
Uranium Capital		Energy Technology, Production: Nuclear Energy	
Uranium capital discard rate		Energy Technology	
Uranium Investment rate		Energy Technology	

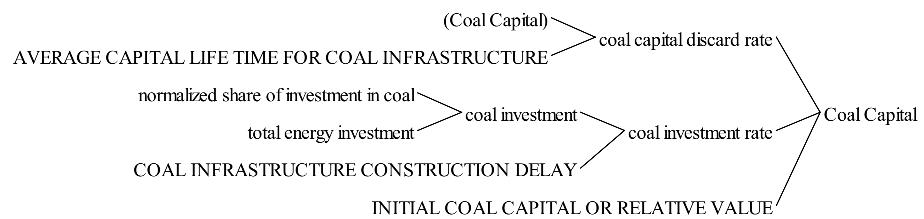
Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Average capital life time per Coal	Constant	Estimated
Average capital life time per Natural Gas	Constant	Estimated
Average capital life time per Renewable Resources	Constant	Estimated
Average capital life time per Uranium	Constant	Estimated
Coal production delay	Constant	Estimated
Initial Coal Capital or Relative value	Constant	Estimated

Initial Natural Gas Capital or Relative value	Constant	Estimated
Initial Renewable Resources Capital or Relative value	Constant	Estimated
Initial Uranium Capital or Relative value	Constant	Estimated
Natural gas production delay	Constant	Estimated
Nuclear production delay	Constant	Estimated
Renewable resources production delay	Constant	Estimated

Functional Explanation

Figure 31: Sketch of the main factors influencing Coal Capital



Coal Capital accumulates *Coal Investment* and capital discard rate:

> Coal Capital=INTEG(+coal investment rate-coal capital discard rate),
> INITIAL (INITIAL COAL CAPITAL OR RELATIVE VALUE)

A delay is considered for capital installation. This changes according to the energy source considered (8 years are assumed to be necessary to plan, design and build a medium to large size coal fired-plant). The actual investment in coal infrastructure and production capacity is calculated as:

> coal investment rate= coal investment/COAL PRODUCTION
> DELAY

Similarly, the discard rate depends on the exogenously defined capital lifetime of capital.

The same structure is used to calculate natural gas, renewable resources and nuclear capital.

Energy Technology

Purpose and Approach

The Energy Technology module represents average technology level of each energy source. Technology increases with investment and decreases with capital discard.
The technology module is built as a co-flow of the Energy Capital module.

Explanation

Major Assumptions

- Energy resources technology is a co-flow of energy capital;
- Technology improvement depends on investment, energy source price and technology improvement cost.

Input Variables

Variable Name	Module of Origin
Coal Capital	Energy Resources Capital
Coal capital discard rate	Energy Resources Capital
Coal Investment rate	Energy Resources Capital
Natural Gas Capital	Energy Resources Capital
Natural Gas capital discard rate	Energy Resources Capital
Natural Gas Investment rate	Energy Resources Capital
Relative Coal Price	Energy Prices
Relative Natural Gas Price	Energy Prices
Relative Nuclear Price	Energy Prices
Uranium Capital	Energy Resources Capital
Uranium capital discard rate	Energy Resources Capital
Uranium Investment rate	Energy Resources Capital

Output Variables

	Module of Destination		
Variable Name	In the Same Sector	In Other Energy Sectors	In Other Sectors
Coal average Energy technology level		Production: Coal	
Natural Gas average Energy technology level		Production: Natural Gas	
Uranium average Energy technology level		Production: Nuclear Energy	

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Coal Effect of Energy Price on Energy Tech Advancement Table	Table Function	Estimated
Coal initial energy capital	Constant	Estimated
Coal initial average energy level of technology	Constant	Estimated
Natural Gas Effect of Energy Price on Energy Tech Advancement Table	Table Function	Estimated

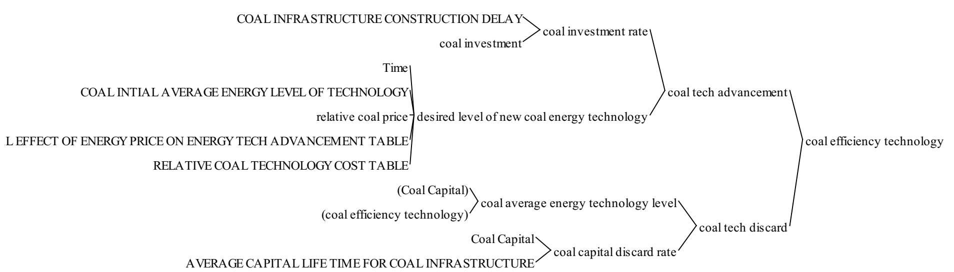
Natural Gas initial energy capital	Constant	Estimated
Natural Gas initial average energy level of technology	Constant	Estimated
Relative coal technology cost table	Table Function	Estimated
Relative natural gas technology cost table	Table Function	Estimated
Relative Uranium technology cost table	Table Function	Estimated
Uranium Effect of Energy Price on Energy Tech Advancement Table	Table Function	Estimated
Uranium initial energy capital	Constant	Estimated
Uranium initial average energy level of technology	Constant	Estimated

Functional Explanation

The structure used to represent technology improvement for coal, natural gas, renewable resources and nuclear power, is identical. The process used to model *Coal Average Energy Technology Level* is here presented.

Coal Technology

Figure 32: Sketch of the main factors influencing Coal Technology



The variable Coal Average Energy Technology Level represents technology improvement for coal exploration, development and recovery. It is calculated as coal efficiency of technology divided by *Coal Capital*:

> coal average energy technology level= Coal Efficiency Technology/Coal Capital

Coal Efficiency Technology is a stock that accumulates *Coal Technology Advancement* and discard. Both flows are influenced by investment and discard rate respectively.

The flow *Coal Technology Advancement* is also influenced by the *Desired Level of New Coal Energy Technology*:

> coal tech advancement= coal investment rate*desired level of new coal energy technology

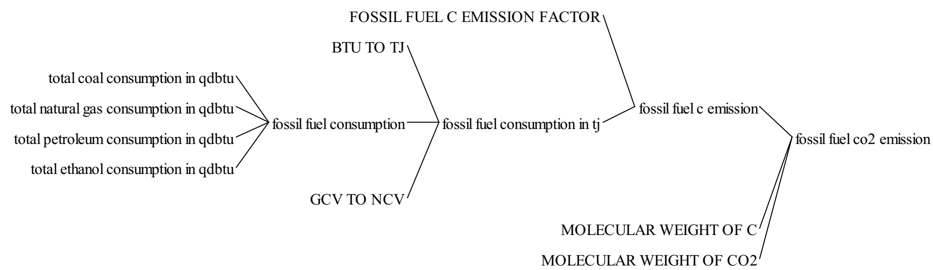
The *Desired Level of New Coal Energy Technology* is calculated taking into consideration investment, energy source price and technology improvement cost:

desired level of new coal energy technology= COAL INTIAL AVERAGE ENERGY LEVEL OF TECHNOLOGY/RELATIVE COAL TECHNOLOGY COST TABLE(Time)*COAL EFFECT OF ENERGY PRICE ON ENERGY TECH ADVANCEMENT TABLE(relative coal price)

Fossil Fuel and GHG Emissions

Fossil Fuel Emissions

Figure 33: Sketch of the main factors influencing Fossil Fuel CO_2 Emissions



Purpose and Approach

The Fossil Fuel Emissions module calculates fossil fuel emissions for CO_2, N_2O, SO_X and CH_4 generated by the burning of fossil fuel (i.e. consumption). The calculation of emissions is based on projected fossil fuel consumption and physical conversion factors.

Explanation

Major Assumptions

- CO_2, N_2O, and CH_4 are the chief determinants of greenhouse gas generation;
- Conversion factors used to calculate emissions out of fossil fuel consumption are constant.

Input Variables

Variable Name	Module of Origin
Coal Production Rate	Production: Coal
Effective US oil import	Demand and Import: Oil
Natural Gas Production rate	Production: Natural Gas
Net natural gas imports in BCF	Demand and Import: Natural Gas
QDBTU to BCF	Demand and Import: Natural Gas
QDBTU to MB	Demand and Import: Oil
QDBTU to MST	Demand and Import: Coal
US Total Oil Production	Demand and Import: Oil

Output Variables

Variable Name	Module of Destination		
	In the Same Sector	In Other Energy Sectors	In Other Sectors
Fossil fuel CH_4 emission	U.S. GHG Emissions and Footprint		
Fossil fuel N_2O emission	U.S. GHG Emissions and Footprint		
Fossil fuel CO_2 emission	U.S. GHG Emissions and Footprint		
Fossil fuel SO_X emission	U.S. GHG Emissions and Footprint		

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
BTU to TJ	Constant	Intergovernmental Panel on Climate Change (IPCC)
FOSSIL FUEL C EMISSION FACTOR	Constant	IPCC
FOSSIL FUEL CH4 EMISSION FACTOR	Constant	IPCC
GCV to NCV	Constant	IPCC
N IN N_2O TO C RATIO	Constant	IPCC
N TO N_2O WEIGHT	Constant	IPCC
Molecular weight of C	Constant	IPCC
Molecular weight of CO_2	Constant	IPCC
QDBTU to BTU	Constant	IPCC
SO_X COEF	Constant	IPCC

Explanation

Functional Explanation

In this module, fossil fuel emissions are calculated by converting consumption of oil, coal and gas into CO_2, N_2O, SO_X and CH_4 emissions equivalent.

Fossil Fuel SO_X Emission

The emission of SO_X from burning fossil fuels is calculated as the total consumption of energy from fossil fuels times the SO_X emissions per BTU of fossil fuels burned:

```
fossil fuel sox emission= SUM(total energy burned[fossil
    fuel!]*SOX COEF[fossil fuel!])
```

Fossil fuel CH_4 emission

Fossil fuel CH_4 emissions are calculated as total fossil fuel consumption multiplied by the CH_4 emission per TJ of fossil fuels used:

```
fossil fuel CH4 emission= SUM(fossil fuel consumption in tj[fossil
    fuel!]*FOSSIL FUEL CH4 EMISSION FACTOR[fossil fuel!])
```

Fossil fuel N_2O emission

As for the CH_4 emissions, N_2O emissions are obtained as the *fossil fuel C* (carbon) *emission* multiplied by a conversion factor that represents the equivalent of one unit of C emission in N_2O:

```
fossil fuel N2O emission= fossil fuel c emission*N IN N2O TO C
    RATIO*N TO N2O WEIGHT*KG PER TON
```

Fossil fuel CO_2 emission

The total emission of CO_2 from the burning of fossil fuels is calculated as *fossil fuel C emission* multiplied by the *molecular weight of CO_2*, divided by the *molecular weight of C*. It is assumed that all *C* becomes CO_2, even though a small percentage becomes *CO* and CH_4:

```
fossil fuel co2 emission= fossil fuel c emission*44/12
```

GHG Emissions and Footprint

Purpose and Approach

The GHG Emissions and Footprint module calculates fossil fuel greenhouse gas emissions in CO_2 equivalent and, for the US only, the effect of fossil fuel emissions on mortality. It also calculates the *American Per Capita Footprint*, *United States Footprint Relative to Biocapacity*, and the *America Footprint Relative to World Sustainable Footprint*.

The ecological footprint of a person measures the biologically productive areas necessary to continuously provide the resources needed to maintain his/her current lifestyle and to absorb the wastes he/she produces. As illustrated in Figure 36, national footprint depends on the size of the population and on the per capita (PC) footprint. Various elements and habits contribute the size of the per capita footprint. These elements can develop at different paces, depending on the specific characteristics of the country analyzed. In the example of Figure 36, the only component of the PC footprint that is assumed to change substantially in the time horizon of the simulation is the CO_2 footprint. The other components are assumed to be constant. When there is evidence that those components could significantly change over the time horizon of the simulation, they can be treated as endogenous or represented by time dependent functions.

The US GHG Emissions and Footprint module is here presented.

Explanation

Major Assumptions

- The available biocapacity is constant;
- The PC biocapacity available worldwide is exogenous;
- Apart from per capita footprint from *CO_2* from fossil fuels, the other factors affecting the per capita ecological footprint are constant.

Input Variables

Variable Name	Module of Origin
Fossil fuel CH_4 emission	U.S. Fossil Fuel Emissions
Fossil fuel CO_2 emission	U.S. Fossil Fuel Emissions
Fossil fuel N_2O emission	U.S. Fossil Fuel Emissions
Real GDP at factor cost	Investment
Total land area	Land
Total population	Population

Output Variables

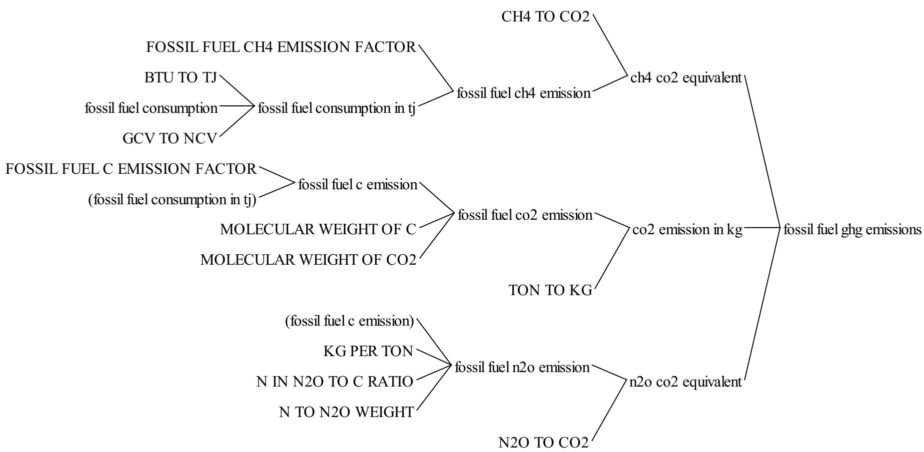
	Module of Destination		
Variable Name	In the Same Sector	In Other Energy Sectors	In Other Sectors
Effect of fossil fuel emissions on mortality			Life Expectancy
Fossil fuel GHG emissions		Carbon Cycle	

Constants and Table functions

Variable Name	Type of Variable	Source for Estimation
Available Biocapacity	Constant	WWF (World Wildlife Fund) data
CH_4 TO CO_2	Constant	IPCC
N_2O TO CO_2	Constant	IPCC
PC area used for food, row materials, infrastructures and housing	Constant	WWF (World Wildlife Fund) data
PC biocapacity available worldwide	Time Series	WWF (World Wildlife Fund) data
Effect of fossil fuel emissions mortality table	Table Function	AEA Technology Environment, European Commission
Reference pc area used to store CO_2	Constant	WWF (World Wildlife Fund) data
Reference CO_2 Emission Level	Constant	WWF (World Wildlife Fund) data

Functional Explanation

Figure 34: Sketch of the main factors influencing Fossil Fuel GHG Emissions



Fossil fuel greenhouse gases emissions in CO_2 equivalent

The total annual emissions of greenhouse gases by the country, in CO_2 equivalents, is calculated as the sum of CO_2 emissions, CH_4 emissions, and N_2O emissions, the last two in CO_2 equivalents:

> fossil fuel ghg emissions= co2 emission in kg+ch4 co2 equivalent+n2o co2 equivalent

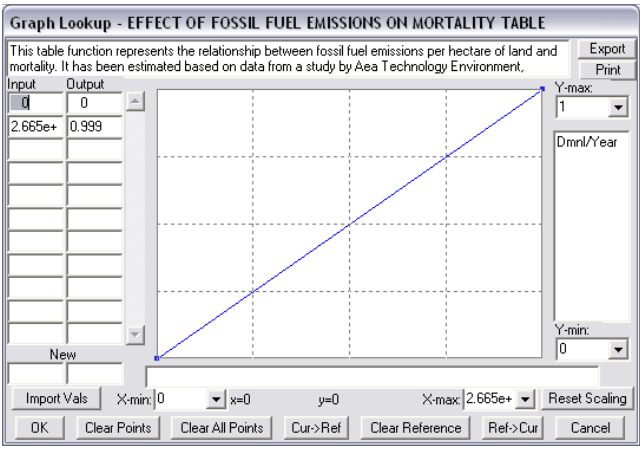
Effect of fossil fuel emissions on mortality

The *effect of fossil fuel emissions on mortality* is calculated based on the *EFFECT OF FOSSIL FUEL EMISSIONS MORTALITY TABLE*, using as input the *CO_2 emissions per hectare*, which is assumed to be a good proxy for PM10 emissions:

> effect of fossil fuel emissions on mortality=(EFFECT OF FOSSIL FUEL EMISSIONS ON MORTALITY TABLE(co2 emissions per hectare*local conditions pollution adjustment))

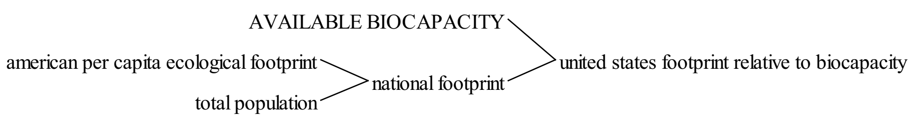
The *EFFECT OF FOSSIL FUEL EMISSIONS MORTALITY TABLE* represents the relationship between fossil fuel emissions per hectare of land and mortality (Figure 35). It has been estimated based on data from a study by AEA Technology Environment, commissioned by the EU.

Figure 35: Assumed Relationship between fossil fuel emissions per hectare of land and mortality.



Per Capita Footprint from CO_2 from Fossil Fuels

Figure 36: Sketch of the main factors influencing US Footprint relative to Biocapacity



The per capita ecological footprint in hectares, due to emissions from the burning of fossil fuels (*per capita footprint from co2 from fossil fuels*), is calculated as the reference per capita footprint from fossil fuels multiplied by the relative level of CO_2 emissions:

> per capita footprint from co2 from fossil fuels= PC FOOTPRINT FROM REFERENCE CO2 FROM FOSSIL FUEL*relative co2 emission

The CO_2 footprint is the only component of the *per capita ecological footprint* that is assumed to change substantially in the time horizon of the simulation.

American Per Capita Ecological Footprint

The *American per Capita Ecological Footprint* represents the productive land and water one person requires to produce the sustainable resources he or she consumes and to absorb his/her sustainable wastes, all using prevailing technology. It is calculated as the sum of per capita footprint from various sources, assuming that only the CO_2 from fossil fuels per capita footprint varies over time:

> American per capita ecological footprint= per capita footprint from co2 from fossil fuels+"PC AREA USED FOR FOOD, ROW MATERIALS, INFRASTRUCTURES AND HOUSING"

National Footprint

The *national footprint* represents the amount of productive land and water the country requires to produce the sustainable resources it consumes and to absorb the waste it generates, using currently available technology. It is calculated as the *Total Population* times the *American per Capita Ecological Footprint*:

> national footprint= total population*American per capita ecological footprint

The *United States Footprint Relative to Biocapacity* is an indicator of the long-term sustainability, given nature's biologically productive capacity. It is calculated as the *National Footprint* divided by *Available Biocapacity*.

America Footprint Relative to World Sustainable Footprint

This variable in an indicator of the proportion of the world's per capita biocapacity, used per person in the country. It is calculated as the ratio of the *American per Capita Ecological Footprint* and *PC BIOCAPACITY AVAILABLE WORLDWIDE TABLE* (using as input *Time*):

> america footprint relative to world sustainable foot print = american per capita ecological footprint/PC BIOCAPACITY AVAILABLE WORLDWIDE(Time) References