Energy Economics xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

An integrated approach to energy prospects for North America and the rest of the world

Andrea M. Bassi [a,b,*], Robert Powers [c], William Schoenberg [c]

[a] Millennium Institute, 2111 Wilson Blvd, Suite 700, Arlington, VA 22201, USA
[b] University of Bergen, Postboks 7800, 5020 Bergen, Norway
[c] SUNY-ESF, 1 Forestry Drive, Syracuse, NY, USA

ARTICLE INFO

Article history:
Received 9 January 2009
Received in revised form 13 April 2009
Accepted 18 April 2009
Available online xxxx

Keywords:
Energy policy
Integrated modeling
Scenario analysis
Renewable energy
Vehicle efficiency
Oil supply

ABSTRACT

Many international organizations and research institutions have released recently unequivocal scenarios on energy's future prospects. The peak in global oil production is likely to happen in the next ten to fifteen years, if it hasn't already happened, and decisions to be made in the near future are likely to have large impacts on our quality of life in the coming decades. This study presents an integrated tool for national energy planning customized to North America. The authors analyzed the impact of world oil production on economic, social and environmental indicators. Two cases of global ultimate recoverable oil reserves are considered, a low and medium estimate within current research. Three sets of policy directions were chosen: Business As Usual (Market Based), Maximum Push for Renewables, and Low Carbon Emissions. Results of the simulations show that without restrictions on emissions coal becomes the dominant energy in the longer term. On the other hand, if US policymakers are able to effectively implement the necessary polices, such as a 20% RPS by 2020 and increased CAFE Standards, along with increased energy conservation and efficiency, the medium to longer-term economic impacts of a global peak in oil production can be mitigated, while a sustained reduction in emissions would require a larger effort.

1. Introduction

Energy is the foundation of every aspect of our “Global Economy” (Hall et al., 1986). Without adequate actions aimed at preserving energy availability, the well-being of our increasingly urbanized, industrialized and growing world population faces the prospects of a host of severe issues including: a reduced standard of living, declining access to food (Pimentel, 2008) and clean water supplies (Gleick et al., 2006), and the contraction of global trade and GDP (IPCC, 2007a,b,c).

In the next decade and beyond, energy-related decisions will be made and polices enacted at national levels that will have direct consequences for large segments of the human population and for the global environment as a whole. These decisions, such as those to be taken at the upcoming 2009 UN Summit on the Climate Change Convention (UNFCCC—COP15), will directly and indirectly impact energy and resource availability, human well-being, and even the survival of the environment as we know it, on which all economies ultimately depend. Among other organizations, the Association for the Study of Peak Oil and Gas (ASPO) believes that the consequences of a peak and subsequent decline in conventional global oil production may cause unexpected and dire consequences for our society, economy, and environment.

Many energy studies focus on how to best meet the increasing future energy demand with available energy, and generally this approach optimizes energy flows while minimizing costs (e.g. MARKAL (Fishbone et al., 1983; Loulou et al., 2004), MESSAGE (Messner et al., 1996; Messner and Strubegger, 1995), POLES (CNRS, 2006), and PRIMES family of models (NTUA, 2005, 2006a,b)). Fewer studies investigate oil depletion in isolation (Sterman, 1981; Sterman et al., 1988) and energy-economy interconnections (Fiddaman, 1997; Bassi, 2008). Others study the net energy gain of various energy sources (Hall et al., 1986; Cleveland et al., 1984; Odum, 1971). The American chapter of ASPO (ASPO-USA) believes that all of these energy-related factors should be included in an integrated simulation model.

Unfortunately, very few studies investigate explicitly and comprehensibly how the energy sector connects to society, the economy, and the environment. Not may people are used to thinking in terms of systems, which includes looking at the causal relations and feedbacks existing among the above mentioned sectors. We aim here to apply systems thinking to energy issues at the global, regional, and national level.

Specifically ASPO suggests that we should look at the impact of energy availability on the economy in terms of the productivity of capital (e.g. by embedding energy as a component of the sector Cobb–Douglas production functions), the availability of resources as a constraint for

---

* Corresponding author. Millennium Institute, 2111 Wilson Blvd, Suite 700, Arlington, VA 22201, USA. Tel.: +1 571 721 8275; fax: +1 703 841 0050.
E-mail address: ab@millennium-institute.org (A.M. Bassi).

0140-9883/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.eneco.2009.04.005

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

production, energy imports and their impacts on national accounts, as well as the effects of energy expenditures on households accounts. Another cultural issue is the relation of necessary investments in energy acquisition to disposable income (Hall et al., in Pimentel, 2008).

The environment is also closely connected to energy. Water availability is frequently an issue in energy production (e.g. tar sands and biofuels), and air and water pollution are created when we burn fossil fuels for energy, as well as when we build renewable energy infrastructure. The International Energy Agency (IEA) in the World Energy Outlook 2006 (IEA, 2007) concludes that in order to keep emissions at current levels by 2030, we will have to have major breakthroughs in the technologies associated with energy production and consumption, all the while keeping costs low and affordable. The IEA also points out that the options considered in their Beyond the Alternative Policy Scenario (BAPS) simulation have no precedents in history and should be developed quickly and taken to scale in order to actively contribute at the global level.

Luckily many excellent detailed sector models exist, such as NEMS (EIA, 2003), but comprehensive frameworks are either not available to the public or discarded due to their complexity (e.g. black boxes) (Bunn and Larsen, 1997). ASPO-USA aims at putting these studies together to create an open-source, transparent, and comprehensive model which:

- Raises awareness of fossil-fuel depletion, its implications for global policy makers, and its impacts on the general public.
- Analyzes and quantifies the consequences of fossil-fuel depletion on society, economies, and environment.
- Highlights new market opportunities in the energy field.
- Helps us investigate and understand the impacts of different policies (e.g. rates of adoption for various mixes of renewable/fossil/nuclear sources) under different future scenarios.

In order to involve a broad range of stakeholders and stimulate discussion on the above, ASPO-USA decided to adopt an approach that facilitates participation and consensus building by encouraging open discussion with various stakeholders to test their assumptions and draw conclusions about energy issues. This process will facilitate strategy and policy development by simulating possible impacts of alternative policy choices and strategic options.

In order to reach these objectives, the model should have the following characteristics:

1. *Accessibility:* the model is open source and is available to interested parties via the Internet for running remotely or for downloading, and there is no requirement to invest in expensive or proprietary software to run the model.
2. *Transparency*: the user interface permits clear visibility into, and understanding of, the underlying components of the model, their relations to each other, and to the model's database.

Therefore, the purpose of the modeling effort is to identify what the main feedback loops underlying the system are and to generate forward-looking scenarios of energy use at the world, regional, and national levels, in which various policy decisions may be made that affect the outcome of the scenarios generated. Ultimately, the model should be a credible and useful policy-development tool that will be available to decision-makers in governmental and business arenas, to other non-profit organizations, and to members of the public. These and other users not be experts at complex systems modeling, but it will help them better understand the consequences and implications of energy-related decisions and policy directions.

This paper focuses on analyzing energy issues and their consequences on the economies, societies, and environment of North America (USA, Canada and Mexico). The project investigators have developed and applied a System Dynamics-based model, which uses a set of differential equations based on the best available sector models as its mathematical foundation. T21-North America (T21-NA) is based on the experience gathered by the Millennium Institute building a number of customized T21 models over the last 25 years, and by the State University of New York, College of Environmental Science and Forestry (SUNY-ESF), whose faculty have produced some of the best research in the field of net energy and systems ecology. The model is built up on a set of causal relations that eventually create feedback loops among different modules and sectors. These relations are based on established laws of physics, thermodynamics and on economic theories. Also they are based on observed social and political relations to the largest extent possible. The model incorporates the best sector-studies available to date into a one single modeling framework, and it is calibrated using best-available data to ensure it reflects real-world conditions accurately (see the section "Features and structure of the model" for more details).

The results are disseminated to stakeholders through a user interface specifically developed for the project. It allows users to examine the model and interpret the results in several ways, depending on their preferred learning style. The full model can be viewed and explored, allowing users to see the key relations through the equations used or through schematic causal tracing trees. Specific feedback loops and sectors have their own visualizations with graphs of their behavior over time, which is frequently much easier to understand for lay-persons then the model sketches in Vensim. Custom simulations can also be run through the interface and compared to the simulations created by the project investigators.

Complexity is not a goal of the project. ASPO-USA and the two main investigators believe that the model should incorporate complexity only to the extent that it improves the reliability, accuracy, and credibility of the model's results. It is our belief that overly complex models tend to confuse the subject and cloud the understanding of the systems that they strive to represent, in particular the relationship of the system represented to the rest of the global system. Therefore, the principal investigators have spent much time and effort ensuring that the model is as simple and as straightforward as reality allows it to be, while preserving the key interlinkages.

2. Research questions

This study aims to analyze various energy-related issues in the context of an integrated model that incorporates the relations of the energy sector to the broader economic, social, and environmental framework. The main research questions for this project are:

- What are the likely results of continuing current energy use on the availability of conventional energy sources and on the rest of the economy?
- What are the possibilities of expanding the use of non-traditional fossil fuels (e.g. tar sands or shale oil) to meet liquid fuel needs?
- What are the net-energy consequences associated with a variety of probable mixes of energy sources (i.e. conventional fossil fuels, non-traditional fossil fuels, biofuels, nuclear, and renewable, for example)?
- How would different alternative energy sources affect other aspects of overall economic, social, and environmental conditions, such as the impact of different biofuels on food production, water availability, and deforestation?
- What would be the amounts of GHG emissions under different assumptions and approaches; will sequestration programs be effective and what are their direct and indirect effects and costs; and what effect control of such emissions would have on energy availability?
- To what extent will endogenous factors, such as rising energy prices and increasing scarcity, create enough incentives to support a shift to sustainable/renewable energy, how will currently discussed energy policies (e.g. CAFE and RPS) help the transition, and how much exogenous political action is needed to achieve a transition to a sustainable future? Indeed, is a sustainable future possible?

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

Among other research questions and energy-related issues, the economical consequences of an early petroleum production peak and energy return on investment will be addressed in more detail. In considering these and other possibilities, the model generates scenarios that show the results across all the key indicators for the economy, society, and environment, so users can get a full picture over a long time frame of the likely results, both positive and negative.

Petroleum is especially important among energy sources because of the magnitude of its current use, it is extremely energy dense and easily transportable (Cleveland, 2005), and its future supply is worrisome (Campbell and Laherrère, 1998). The key issue is not when we will run out of oil, but rather when demand will seriously outstrip supply for biophysical reasons. Without a massive worldwide recession, demand will continue to increase as human populations, petroleum-based agriculture, and economies all continue to grow (IEA, 2007). The production of oil and gas has been growing on average several percent a year since the early 1900s, but since there are finite (on a time scale relevant to society) reserves this cannot continue indefinitely (Campbell and Laherrère, 1998; Heinberg, 2003). The point of maximum production of an oil field or region, such as a country or the world, is known as peak oil. It is important to note that this isn't simply a theoretical concept, it actually occurred in the United States in 1970 as well as in some 60 (of 96) other oil-producing nations (Hubbert, 1974; Strahan, 2007). Several prominent geologists have suggested that it may have occurred already for the world, although that is not yet clear (e.g. Deffeyes et al., 2005; EIA, 2007a,b; IEA, 2007).

Since markets have to balance, oil production plus the use of inventories (collectively, supply) will always have to be equal to demand. If potential demand grows while supply remains constant, or even shrinks, prices will increase enough to bring the actual demand down to the level of the available supply. While higher prices may lead to some increases in supply, the biophysical realities of peak oil mean that past a certain point, no matter the prices, production cannot be increased. At this point we will enter the second half of the age of oil (Vidal, 2005). The first half was one of year by year growth, the second half will be of continued importance but year by year decline in supply, with possibly an “undulating plateau” at the top. Natural gas may help ease the tradition and buffer the impacts for a decade or so. When the decline in global oil production begins, we will see the “end of cheap oil” and a very different economic climate that can no longer assume continuing access to cheap energy (Hall et al., in Pimentel, 2008).

An equally important issue is that of energy return on investment (EROI), a concept born from physics (Hall et al., 1986). It is the energy returned from an activity compared to the energy invested in that process (Cleveland, 2005). The basic equation is:

$$\text{EROI} = \frac{\text{Energy gained from an activity}}{\text{Energy used in that activity}}$$

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.

3. Features and structure of the model

Various models can plausibly be used to generate the analysis needed for the investigation of the impacts of the transition through the oil peak, but not all energy models are appropriate. Indeed, together with the necessity of including models that generate data at a proper level of aggregation and within the selected boundaries, some crucial characteristics should be attentively considered.

First, it is recommended to avoid relying exclusively on historical correlations. Though we can learn a lot from them when building the model and analyzing the results, they could be altered in the future by nonlinearities and constraints. In other words, the past may not be anything like the future. Therefore it is too risky to construct a model about the future based totally on the past and the common linear relations. A better way to construct this model would be to use structural relations that replicate the causal structure of the processes modeled and represent physical delays (e.g. time required to develop an oil field) and other non-linearities related to the transition explicitly. Second, given the imperfect information, uncertainty, and distributed decision-making peculiar to the energy and economy systems, it would be wise to add to the modeling framework behavioral components, which represent the information available to actors and the procedures they use to process it and formulate decisions. If the model is to respond to changes in the environment in the same way that real actors do, this bounded rationality should be incorporated (Morecroft, 1983; Simon, 1979). Finally, the behavior of the model should be generated, so as to consider changes in any variable of the areas of investigation considered, account for feedback effects, and produce consistent results.

In addition to these general considerations, a model linking energy to the economy, society and the environment that will be used in medium and long-term policy planning should include at least the following specific features (and their causes) as endogenous components:

1. Population: The total population of a country helps determine important social, economic and environmental indicators. Income, educational levels, and access to water, electricity, and many additional interconnected factors all define population dynamics. As one of the primary causes of energy demand, population should be modeled explicitly. We are also interested in per capita energy resources.
2. GDP: A healthy economy can support investments in various sectors and provide the means to afford energy or the transition investments needed. Households have to be able to sustain their standards of living while supporting the Government through taxation, stimulating the economy through consumption, and investing in promising industries. Since national policies drain resources from the main actors in the economy (Government, households, firms, rest of the world) and energy prices have a negative impact on it, an explicit macroeconomic representation is needed.
3. Technology: Among others, energy efficiency (demand side) and the ultimate recoverable resource (supply side) depend significantly on technological development. As for the latter, usually only 40 to 50%

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

(depending on the geological characteristics of the reservoirs) of oil-in-place can be recovered economically with current technology, but the fraction recoverable has been rising and may rise substantially in the future if technology continues to improve, but higher recovery rates, up to the ultimate limit of just below 100%, are likely to become more expensive.

4. Energy prices: Because energy prices have a strong influence on energy demand and on the incentives for exploration and development of fossil fuels and technological improvement for renewable energy, it must be modeled explicitly. The effects of production costs, supply and demand, and market imperfections, should be incorporated.
5. Energy demand: Energy demand is sensitive to price. As prices rise, the demand for energy will be depressed, and the production of substitutes ("back-stops", Nordhaus, 1973) such as biofuels and heavy oil will be stimulated. The pattern of demand and substitution will have a strong influence on production and investment in exploration and development of fossil fuels too. Delays in the response to changes in demand and in the development of the substitutes industry should be explicit.
6. Non-renewable resources depletion: The total quantity of fossil fuels-in-place is finite. As it is consumed, the quantity remaining inevitably declines, and the marginal cost increases, ceteris paribus. Though improving technology may occasionally offset depletion and cause the real price of oil to decline in certain periods of time, the finite resource base and its depletion must be treated explicitly.

The table below contains spheres and sectors of T21-NA. There are several linkages among the economic, social, and environmental spheres and energy is the core to each one. Within each sphere are sectors and modules, and structural relations that interact with each other and with sectors and modules in the other spheres. None of the spheres function independently, though different versions of T21 may focus more heavily on one or the other of the spheres, depending on the issues being addressed (Table 1).

A brief overview of the structure of T21-North America follows. A fuller description (module by module and variable by variable) of the model can be found in *Modeling U.S. Energy with Threshold 21 (T21)* (Bassi, 2008).

The Economy sphere of T21-NA contains major production sectors (agriculture, industry and services), which are characterized by Cobb–Douglas production functions with inputs of resources (including energy), labor, capital, and technology. A Social Accounting Matrix (SAM) is used to elaborate the economic flows and balance supply and demand in each of the sectors. Demand is based on population and per capita income and distributed among the production sectors using Engle's Curves. This helps calculate relative prices, which are the basis for allocating investment among the sectors. The government sector collects taxes based on economic activity and allocates expenditures by major category, which then impacts the delivery of public services, subject to budget balance constraints. Standard IMF and BEA budget categories are employed, and key macro balances are incorporated into the model. The Rest of the World sector comprises trade, current account transactions, and capital flows (including debt management). Overall oil and natural gas production, consumption, and the resulting export surplus in included to estimate oil and gas import potential for North America. Income distribution and poverty levels are calculated for the United States.

Table 1
Spheres and sectors of T21-North America.

T21-NA—spheres and sectors	
Society and Economy	Energy and Environment
Population sector, 3 modules	Land sector, 1 module
Labor sector, 2 modules	Sectoral energy demand sector, 6 modules
Poverty sector, 1 module	Energy demand and trade sector, 9 modules
	Energy supply sector, 16 modules
	Energy prices and costs sector, 4 modules
Production sector, 4 modules	Energy investments and capital sector, 5 modules
Households sector, 1 module	Energy expenditure, 2 modules
Government sector, 5 modules	Energy technology sector, 1 module
Investment sector, 2 modules	Emissions and climate change sector, 4 modules
Trust funds sector, 2 modules	
Technology sector, 1 module	Rest of the World (ROW) production sector, 4 modules
ROW sector, 2 modules	ROW price and cost sector, 3 modules
	ROW emissions sector, 4 modules
	Canada and Mexico demand and supply sector, 6 modules
	China and India energy demand sector, 2 modules

The Social sphere contains detailed population dynamics by sex and one-year age cohort, health and education programs, and other challenges, such as poverty levels. These sectors take into account, for example, the interactions of family planning, health care and adult literacy on fertility and life expectancy, which in turn determines population growth. Population determines the labor force, which shapes employment. Education, health levels, and other factors influence labor productivity. Employment and labor productivity affect the levels of production from a given capital stock. And these factors all affect the levels of saving for investment and consumption expenditures.

The Environment sphere tracks pollution and other impacts on the environment from production and social activity, and their impact on health, climate change, agricultural production, etc. It estimates the consumption of natural resources—both renewable and non-renewable—and can estimate the impact of the depletion of these resources on production or other factors. In addition, the Environment sphere examines the effects of erosion and other forms of environmental degradation on other sectors, such as agricultural productivity. Energy demand, supply and trade, and pricing and investment are calculated endogenously. Carbon cycling and climate change are included to represent interactions among energy–environment–economy–society components in a more comprehensive way.

The energy sources considered in the model are oil and direct liquid substitutes (including heavy and extra heavy oil and ethanol from corn and sugar cane), natural gas, coal, and electricity (generated from nuclear power, renewable resources—wind, solar, geothermal- and hydroelectric power). Energy modules include:

– *Energy demand* is disaggregated into residential, commercial, industrial and transportation sectors for the US, demand for the energy sources listed above is based on initial energy GDP intensiveness, technology, energy prices and substitution among energy sources. Demand affects, among others, energy production, trade, prices and investments.
– *Energy supply* includes oil, natural gas and coal as primary sources. Electricity is obtained from nuclear power and renewable energy. Energy supply is calculated based on demand, availability of resources (for fossil fuels), capital and exogenous policy interventions. The McKelvey Box (USGS, 1976) is used to define and classify resources, which relate to the energy intensity of resource extraction. Supply impacts, among others, consumption, prices, trade and generation of pollutant emissions.
– *Energy prices and costs* cover oil, gas, coal, nuclear, electricity. Fossil fuels prices are based on reserve and resource availability over the medium and longer term; electricity price is calculated based on the weighted cost of the energy sources utilized to produce it. Energy prices from renewable resources are treated as exogenous inputs and are assumed to decrease by 15% by 2050. Energy prices and costs influence demand, investment, and production in the energy sector, as well as production in the economic sectors.
– *Energy investment* is endogenous for oil, gas, and coal, and exogenous for renewable and nuclear. Investment is based on market profitability (both per each energy source separately and

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

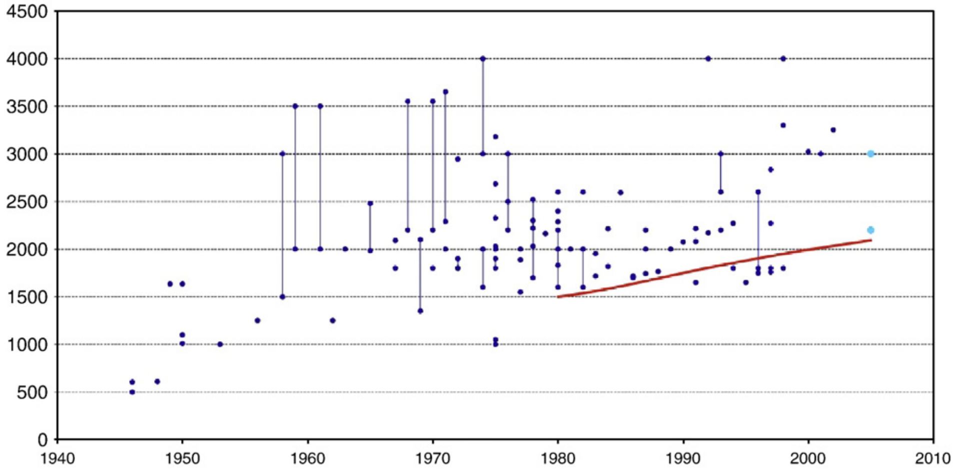

Fig. 1. Estimates of world ultimate recoverable petroleum (Source AAPG 2006) and simulated URR (T21-NA).

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* addresses energy efficiency (for the four demand sectors), exploration, development and recovery (for fossil fuels, separately), and vehicle fuel economy. 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* includes emissions (CO_2, CH_4, N_2O, SO_x, and total greenhouse gasses). Pollution is based on fossil fuel consumption and technology levels; it affects carbon cycle and climate change, as well as life expectancy.

The modules above calculate energy demand for the US, Canada, Mexico, China, India and the rest of the World, and energy supply and emissions for North America and the rest of the World.

4. Definition of the scenarios

A set of assumptions can be simulated with T21-NA to create various scenarios on top of which different policies can be tested. This study was largely carried out before the current economic crisis, but insights emerging from the analysis can be useful to analyze and understand recent events and may shed light on the path to recovery. For this exercise, following the suggestions of ASPO-USA, assumptions are limited to the total ultimate recoverable resource (URR) and scenarios analyzed the implementation of a variety of polices.

ASPO-USA believes that the United States Geological Survey (USGS) low and medium estimations of the URR (USGS, 2000) for conventional oil and natural gas liquids are reasonably on target, considering that one of the biggest exponents of ASPO, Colin Campbell and Jean Laherrère, have estimated the URR to 1.9 trillion barrels for crude oil only (Campbell and Laherrère, 1998). The figure below shows URR estimations from 1945 until 2003. The two dots in 2005 represent the assumptions simulated in the Medium and Low URR scenarios. The red line shows the amount of recoverable reserves as simulated by T21, starting from 1980. In the Low URR case, technology will not allow to recover a lot more oil than we currently expect. Conversely, in the Medium URR case, new discoveries and technology will allow for the recovery of more reserves. Users simulating T21 can decide how much oil reserves and resources are in place at any point in time. For simplicity we analyze three sets of scenarios: one based on the USGS Low 2.2 trillion barrels-, and two based on the USGS Medium Estimate—3 Trillion barrels—(where peak oil takes place in 2020 and where a plateau phase takes place in 2011 and production declines after 2020) (Fig. 1).

The policy choices of T21-NA range across energy, society, economy, and the environment. 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). This paper analyzes three main groups of policy/action options in the context of both the low and medium URR sets of energy availability assumptions: Market Based, Maximum Push for Renewables, and Low Carbon Emissions.

The Market Based simulations serve 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 United States Department of Agriculture (USDA) until 2016 (USDA, 2007). To simulate the introduction of renewables into the market, we use the EIA reference case for renewable energy production, while ethanol production, although endogenously calculated, follows USDA projections.

The Maximum Push for Renewables scenario simulates what would happen if there were large support for bringing renewable energy on line by the Federal Government. It is therefore assumed that a Renewable Portfolio Standard (RPS) of 20% by 2020 is approved by the 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 outlook of the American Council on Renewable Energy (ACORE) is also tested in another scenario in this set. In their Outlook on Renewable Energy in America (ACORE, 2007), non-profit and academic organizations, trade associations, and governmental agencies provide estimations of potential energy production capacity from various renewable energy sources. They state that a total of 635 GW (GW, equal to 1 billion watts) of renewable power capacity can be added to the existing 99 GW by 2025 (ACORE, 2007).

The Low Carbon Emissions scenarios add additional policies on top of the implementation of the 20% RPS: the CAFE Standards will be increased (H.R. 1506 by Rep. Markey) in Emissions Low and Med. And there will be increased electrification of light urban, commuter, and freight rail in the Emissions Trans scenarios. The former assumes that, as proposed by H.R. 1506, new standards for passenger vehicles <10,000 lbs. will be set at 35 mpg by 2018, followed by a 4% increase each year thereafter. The latter originates from conversations with transportation expert Alan Drake and luminary Ed Tennyson, who believe that by following the example of European countries such as France and Germany, the US can add the

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

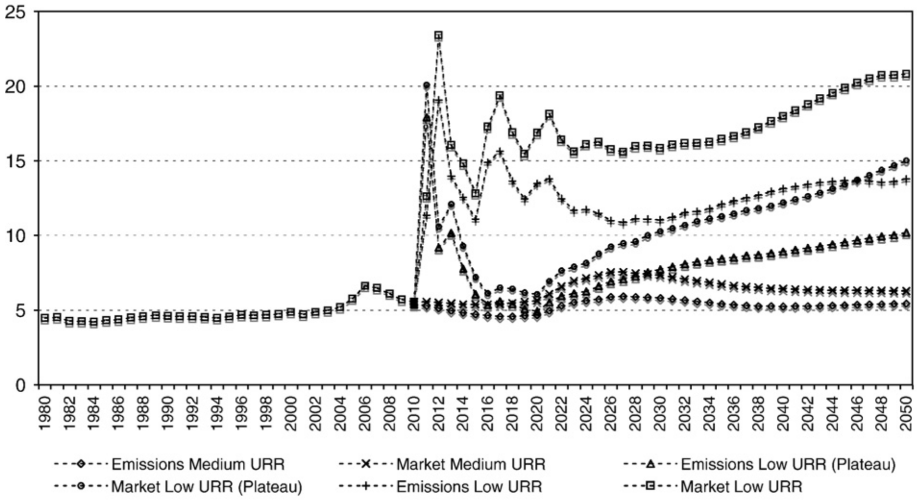

Fig. 2. Comparison of average US energy price (in real USD/Million Btu) simulated by T21-NA under different scenarios.

equivalent of a NYC subway per year in the US starting in 2011 (both for urban rail, commuter and freight transportation).

5. Results

The main differences among the scenarios simulated, which include the assumption that the peak in world oil production will take place in 2011, can be summarized as follows. Energy prices are among the main factors affecting GDP, therefore when oil production turns downwards in 2011 at 29.5 Mb/year (Low URR scenarios), real oil prices 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, this factor, as observed in 1983 and 1984, allows a less energy intensive economy, where energy conservation has taken place, to grow until energy prices start increasing again. In fact, the GDP growth rate turns positive in 2014 and oscillates around zero until the energy transition is fully completed by 2025.

On the other hand, it has to be noted that high energy prices reduce discretionary consumption, which, as shown by the Cheese Slicer later in the paper, can be seen as an indication that quality of life is decreasing.

Over the longer term, though demand is rapidly decreasing following declining supply, oil prices will keep increasing due to the higher cost of extracting oil from the less accessible reservoirs that will become a larger portion of the supply base, reaching $300 in 2050. In fact, the energy return on investment for oil and gas is projected to decline, reaching a ratio lower than 10:1 in 2050 for economically produceable wells.

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, given the delay in capacity building. As a consequence, the average energy price declines and is constantly lower than in the Market Based scenario (by about 18%) after 2020 and throughout the simulation (Figs. 2 and 3).

It has to be noted that when simulating the Renewable (ACORE) and Emissions scenarios, electricity generation from renewable energy sources grows considerably. As a consequence, the average cost of electricity increases (+40% with respect to the Market Based scenario), especially when both ACORE 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. An increase in energy prices with respect to the current level though, will shrink resources for

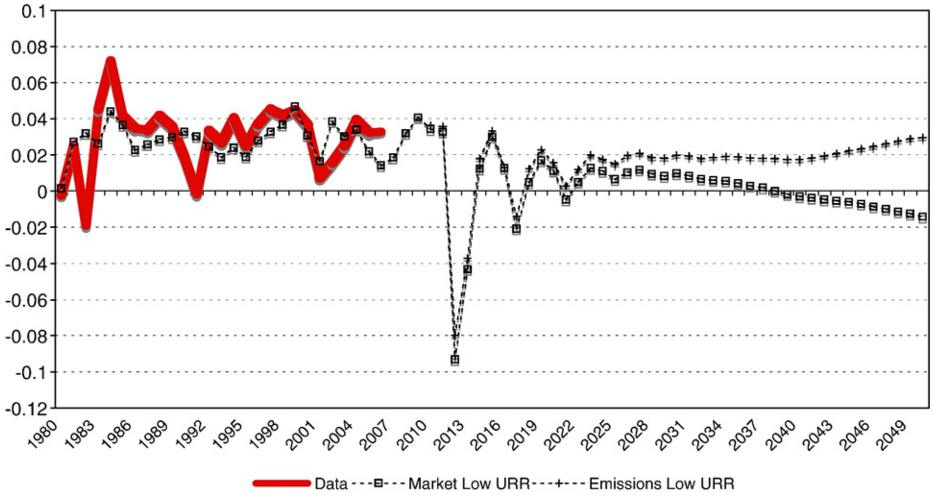

Fig. 3. Comparison of real GDP growth rate simulated by T21-NA under different scenarios and historical data.

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

households and the industry. Also, support to the government is needed to contain debt. For the US 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. The debt GDP ratio is assumed to be maximum three times as much as current level.

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 the growth rate is still higher rate 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 due to increased efficiency. Furthermore, the additional capacity and production of unconventional oil and biofuels will help ease the energy transition, leading to a 15% larger GDP in 2050, due to about +0.3% in growth rate throughout the simulation. 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.

The behavior description and analysis of T21-NA concentrates on energy and its interconnections with the three other sectors: society, economy, and the environment. While the USA part of the model is more detailed in its representation of energy, society, economy and environment; the models of Canada, Mexico and the rest of the world components are mainly focused on energy.

5.1. Society

Total population in the USA is projected to grow by between 32.6% (Market Based Low URR) and 38% (Low Emissions High URR) in the period 2006–2050, reaching 402.5 or 416.7 million people. These figures are in line with the projections from United Nations Population Division. Population growth in the US, especially for the elderly age cohorts, is likely to affect the sustainability of social security and medicare trust funds as indicated by the increase in their share of the population in the breakdown by age cohorts.

By looking at the population pyramid, 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; one of which is the “baby boomer” group which contributes to the growth of the elderly population.

Employment is projected to remain about constant through 2050 in the Low URR scenario (140 M) and increase in the Medium URR case (211 M). Employment is sustained in the former simulation by an increase in fuel prices and a reduction in labor cost, which stimulates the shift back towards a more labor intensive economy.

5.2. Economy

The main components of the Economic sector 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) (Pyatt, 1991; Drud et al., 1986).

A few indicators are shown per each agent:

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

Real GDP at market price in the Low URR case is projected to remain at about its current level in 2050 ($13 trillion, using 2000 as the constant dollar base year) and rise to $44 trillion in the Medium URR scenarios. Even assuming oil field technology will improve when the ratio between demand and supply is very tight, generating an undulating plateau in oil production until 2020, this will not improve the long-term trend of GDP much from the Low URR scenario. It has to be noted that since both Renewable and Emissions scenarios reduce US dependency on oil, GDP will perform better (+5% and +24% in the Low URR case and +13 and +16% in the Medium URR scenarios respectively) (Figs. 4 and 5).

The elasticity of GDP to energy prices is assumed to be a function of the overall energy intensity of the economy. This means that the economy becomes less and less sensitive to energy prices as its efficiency increases. Elasticity in 1980 is set to −0.3, the lowest value among various estimations dating back to the highly volatile early eighties (D. Gately, 2004; S. Brown, 2003), and reaches −0.115 in 2050. Among sectors, agriculture is projected to suffer the least from the increase in energy prices, not because of lower vulnerability of the industry (in fact yield decreases due the increasing cost of energy inputs in the Low URR case) but because of the need to produce agricultural products for domestic consumption. Historical comparison is mainly made with data series published by the International Monetary Fund (IMF) and the Bureau of Economic Analysis (BEA).

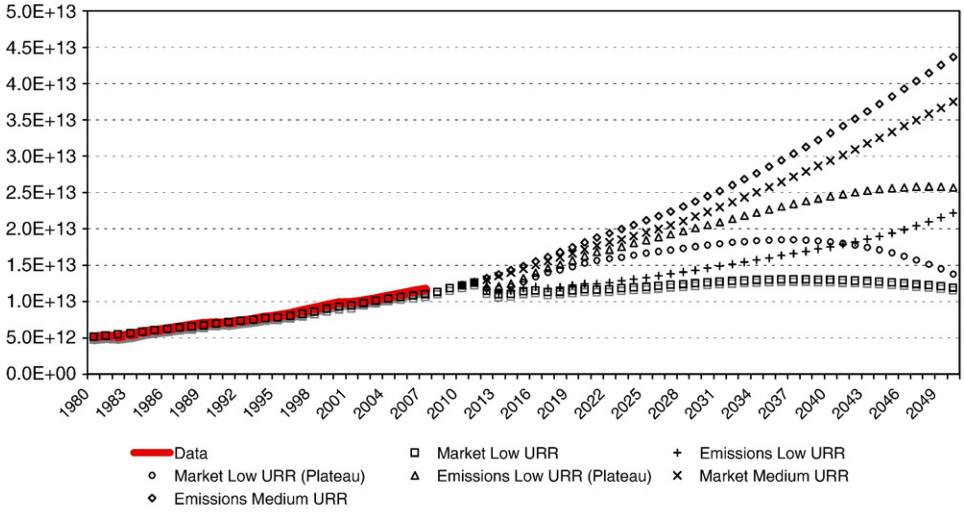

Fig. 4. Comparison of real GDP simulated by T21-NA under different scenarios and historical data.

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

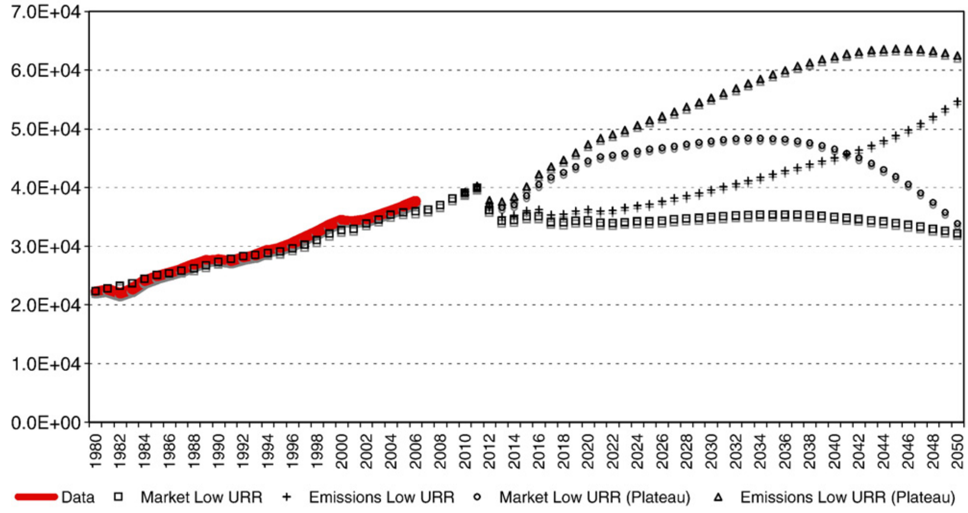

Fig. 5. Comparison of per capita real GDP simulated by T21-NA under different scenarios and historical data.

Nominal Federal government revenues and expenditures generally follow the GDP trend, as the former are obtained though taxation and the latter are allocated based on available revenues. As a consequence, the overall fiscal balance (i.e. revenues minus expenditure) will remain negative throughout the simulation ($−4 trillion and $−12 trillion in the Low and Medium URR respectively), and the continuing deficit will lead to a steady increase in public debt (two or three times higher than GDP in 2050 in the Low and Medium URR scenarios, respectively) and likely also the share of government expenditures allocated to debt service.

The Balance of Payments surplus 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 offset by the growth in the capital and financial accounts 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.

Per Capita GDP follows the behavior of GDP, and households savings are reduced by the increasing energy cost and increasing taxation, especially in the Low URR case. As shown in the figure above, per capita GDP decreases in the base case, as population grows faster than GDP. The projections of T21-NA also show that investing in renewable energy and more efficient transportation reduces energy expenses in the medium to longer term and makes income increase. When actions are not taken timely and the transition beyond oil is delayed (Plateau scenarios), extra measures are required to sustain income growth, which turns negative before 2050.

5.3. Energy and environment

Total energy demand projections indicate very different trends for the different scenarios. As for the Low URR, demand ranges between 71 and 86 QdBtu (Quadrillion British Thermal Units) in 2050, declining after 2011. The Medium URR scenario shows that energy demand increases until 2020 and then levels off due to peak oil and increasing energy prices for a few years. Demand starts growing again in 2032 due to GDP, which increases driven by the substitution for oil, reaching 157 QdBtu in 2050 (Fig. 6).

A more interesting analysis regards consumption by energy source, which towards 2050 shifts from oil (−18%) and gas (−5%), to coal (+10% in the Market Based scenarios), nuclear (+8% in the Low URR scenarios) and renewables (+15% and 25% in the Emissions and Renewable scenarios respectively).

Looking at oil in more detail, the dependency on foreign crude is projected to increase from 65% in 2005 to 70% in 2011 and then decline to 50% in the Low URR case by 2050, while it increases to 90% in the Medium URR scenario over the same period of time. On the other hand, both US and world demand rapidly decrease after production

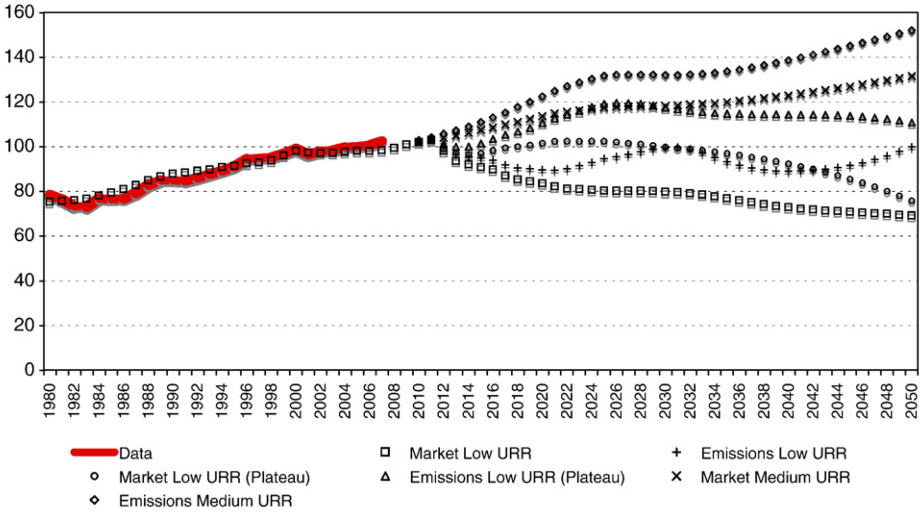

Fig. 6. Comparison of total US energy demand (QdBtu/year) simulated by T21-NA under different scenarios and historical data.

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

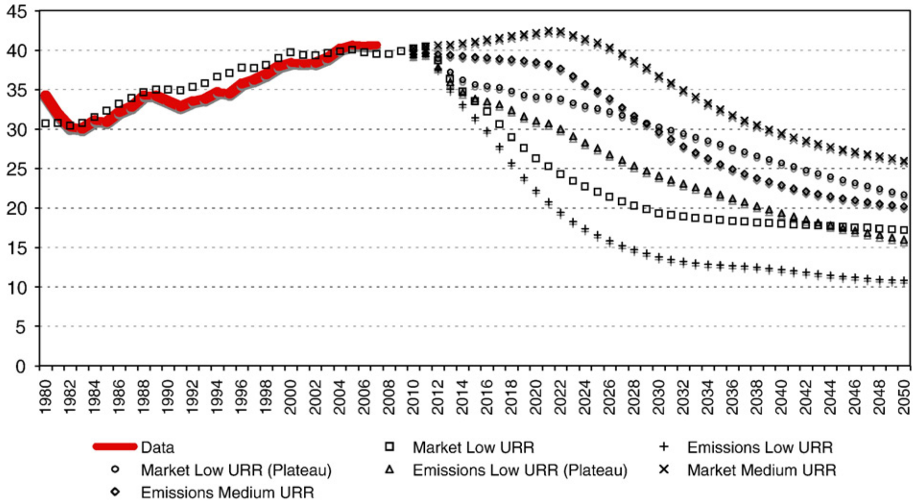

Fig. 7. Comparison of US oil demand (QdBtu/year) simulated by T21-NA under different scenarios and historical data.

starts declining and prices shoot up, respectively in 2011 and 2020 for the Low and Medium URR scenarios (Fig. 7).

Fossil fuel demand from the rest of the world is going to increase at a higher rate than in the US over the next 40 years, mainly due to demand from fast growing countries such as China and India. Specifically, simulated petroleum demand will more than double in China (+224%) and India (+215%), by 2050. Canada will increase its oil consumption by about 60% (Low URR) and 80% (Medium URR) and Mexican consumption will be similar to current level, mainly due to the effect of declining domestic oil production on GDP. Despite increasing fossil fuel demand in Canada and Mexico, production of oil, gas, and coal is projected to decline soon (apart from tar sands that will increase throughout the simulation reaching 1.5 Mbbl in 2050). As a consequence of increasing demand and declining domestic supply, Mexico will become a net importer of oil between 2018 and 2025, while Canada will stop exporting natural gas around 2030 and coal around 2015. The strong economic growth until mid 2008 and the downturn and the subsequent decline in energy prices may both accelerate depletion of recoverable Canadian natural gas and Mexican oil. This is due to (1) high production (driven by high profitability with an expanding economy) and (2) lower investment (driven by higher price competition during periods of declining demand and limited access to capital). Both factors will contribute to the increased dependence of the US on imports from the rest of the world.

While total World CO_2 emissions are projected to increase throughout the simulation, with the only the exception of a few years following peak oil, 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 (Fig. 8).

6. Special topics

6.1. EROI

T21-NA calculates EROI in two different ways: a conventional one (Hall et al., 1986; Cleveland, 1992, 2005) with investments and outputs defining the energy gain, and second one in which energy inputs are a function of energy output and depletion. Results do not vary across different scenarios, as EROI is calculated using longer-term depletion trends, which are based on the total stock of fossil fuel resource, reserve and cumulative production.

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

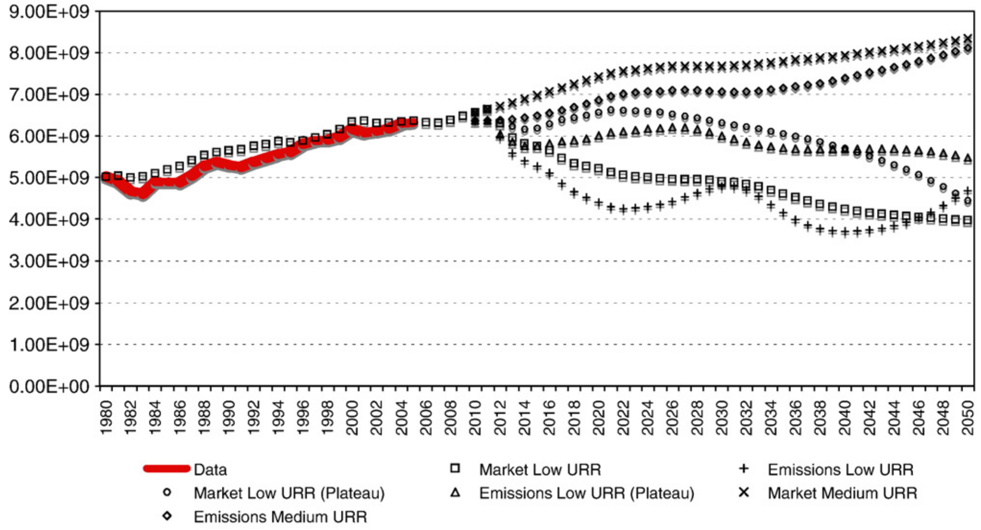

Fig. 8. Comparison of US GHG emissions (tons/year) simulated by T21-NA under different scenarios and historical data.

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

the methods used by Hall and Cleveland (Hall et al., 1986; 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.

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 (Hall et al., 1986; Cleveland, 2005). 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. Using this method for petroleum, we get a result that is fairly consistent in the long term trend with that of Cleveland. Our EROI starts at 25:1 in 1980 and declines rather steadily to around 6:1 in 2050. Our results differ moderately from those of Cleveland in the short terms paths because T21-NA aims at representing medium to longer-term trends. By doing so, instead of computing investment, we rather focus on capital in place, avoiding short-term oscillations due to speculation and energy price volatility. As a result, the long-term trends match up well with Cleveland's study. More specifically, according to T21-NA the direct energy inputs are constantly on the rise; starting off at 1.3 quad in 1980 and reaching 2.2 quads by 2050. The Indirect energy inputs oscillate between 0.3 and 0.4 quads at the beginning of the simulation, falling below 0.1 quads by 2050.

The only differences in the above method for coal are 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. 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 the coal 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 US economic census data (Economic Census, various years). The behavior of the coal EROI is very similar to an updated version of Cleveland's study done by ESF recently. T21 undershoots the updated version of Cleveland's study by about 15%. The model's Coal EROI starts out at around 60 in 1980 and rises to a plateau of approximately 170 in 2015. This behavior is related directly to the coal energy input because coal production remains relatively stable throughout the time span simulated. Our coal energy input first rises steadily from 1980 to the mid 1990s where it proceeds to plateau at around.3 quads. From there it declines steadily to .15 quads in approximately 2020 where it stays until 2050. The reason for the overall decline in Energy Input is that the energy intensity in the coal industry falls over time, due to increases in efficiency (IEA, 2007). These results have limitations and should be viewed as a best case scenario since we do not disaggregate into different coal mining technology types and their future applications. Much of this EROI formulation is based on empircal studies (Cleveland, 1992) and recent historical data (Economic Census, various years) when about a quarter of coal is produced from longwall mines, which are very energy and labor efficient compared to continuous mining operations. In the future, we cannot expect the same results from longwall mines due to resource considerations.

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. 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. 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 (1992 and 2005). 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 petroleum is depletion, which is precisely why we use it to determine the energy inputs of oil and gas production. Our results using this method are similar to the results above, the EROI ranges from 22:1 in 1980 and declines steadily to 13:1 in 2050. The energy input for this method is relatively stable around 1.8 quads until approximately 2005 when it begins to decline slowly to 1.1 quads in 2050. The reason for this late decline is that the energy output of oil and gas falls steadily over time in conjunction with the increasing rate of depletion. It should be noted that this EROI calculation method is sensitive to the initial value of the energy input. Nevertheless, whether we use Cleveland's or ESF's inputs, the projection of EROI is consistent and matches the medium to longer term trend of the respective reference studies. Overall, the two methods show similar long-term trends: the EROI for oil and gas in the US is declining steadily along with production.

7. The Cheese Slicer a conceptual environmental–economic–energy model

The Cheese Slicer is a conceptual model, first realized in Pimentel (2008), by Dr. C. Hall et al., that helps understand what might be the most basic implications of the energy transition on the economic activity of any energy importing country. The US case is presented here and analyzed. The idea underlying of the Cheese Slicer is that the economy requires energy to operate, and in the absence of energy the economy drops. The second premise of this model is that the economy is faced with decisions on how to allocate resources; not only to maintain itself (e.g. perform necessary maintenance on old roads and bridges), but to invest in its own future (money spent on medical research, new roads etc.) so that it may have the potential to grow.

The figure below is a diagram of this model. The large central square represents the economy where, among other things, energy, natural resources, labor and capital, enter the economy, and value added is generated in the form of GDP. In this exercise, the economy is placed within the confines of the world because, like any other entity, it is bound by the laws of nature (Hall et al., in Pimentel, 2008). The arrow labeled “energy” represents the flow of raw unprocessed energy into the economy, which will be upgraded and then used to produce value added. Without this most basic flow, the present economy would turn completely labor dependent and would produce very little to no output (Hall et al., in Pimentel, 2008). The value added produced by the economy, GDP, could be represented as either money or embodied energy. Monetary values are selected for this study, and further research will look at the energetic equivalent of all monetary flows (Fig. 9).

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

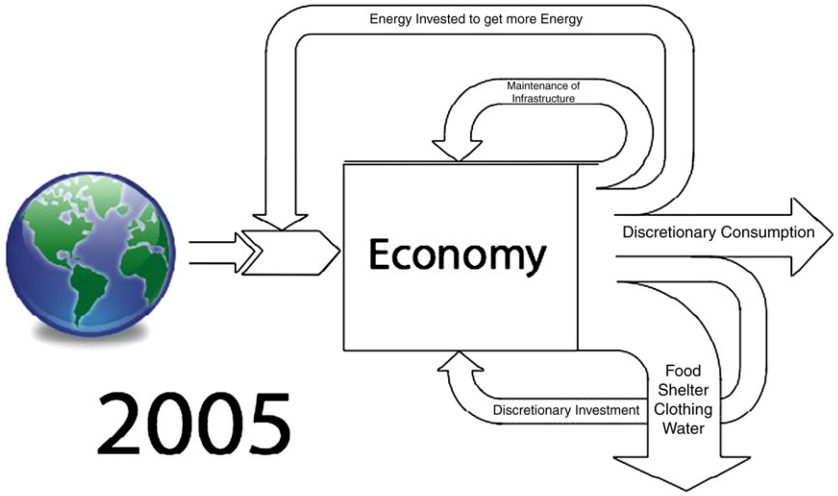

Fig. 9. Conceptual representation of the Cheese Slicer.

There are many paths a single output of the economy (one dollar) can follow. These include investment or consumption, either for necessity (non-discretionary) or for pleasure (discretionary). With T21-NA, we are able to calculate both consumption and investment and simulate them under different assumptions. An explanation of the private sector follows. The Households Accounts module of T21 represents how various economic flows are combined to determine household income, and how this income is split into consumption and savings, part of which eventually becomes investment. For the sake of simplification, in T21 we assume that all the value-added created by

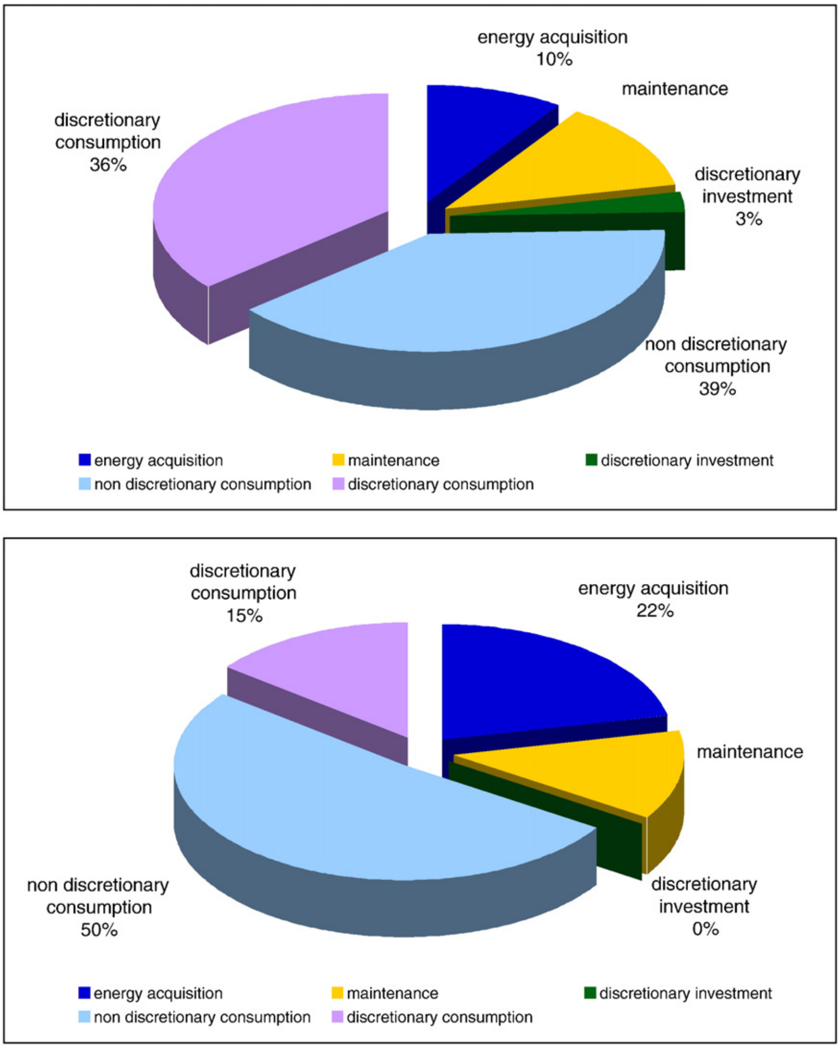

Fig. 10. Cheese Slicer composition in 2007 and 2050.

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

the economy is transferred to households, which pay all domestic taxes and duties. In other words, we do not separately consider that part of the value-added is retained by the firms, taxed by the government, or eventually directly re-invested. Thus, the saving-investment behavior of firms is assimilated to that of households. This assumption seems to be acceptable, considering that households are in most cases the major stakeholders in a firm's activities and have therefore a strong influence on their saving-investment behavior.

Disposable income is calculated as *total households revenue* minus the fiscal withdrawal of the government from households (the government's *budgetary revenue*). Disposable income is then allocated into consumption or savings according to interest rates and Engel's law, which says that the propensity to save is positively related to the level of per capita income. In addition, T21-NA accounts for the effect of energy prices and interest rates as major factors affecting consumption and investment decisions. Non-discretionary consumption is assumed to be a function of total population, while the three categories of investment in the Cheese Slicer are calculated as capital depreciation (maintenance), investment minus depreciation (new investment), and energy investment (energy input).

As energy becomes more expensive, due to the mismatch between demand and supply for oil or due to 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.

The Cheese Slicer shows that the impact of the energy transition beyond oil can have relevant impacts on both households and the industry. The former will be affected by growing energy expenditure, which will reduce discretionary consumption in spite of improved energy efficiency and increasing energy conservation, each of which has investment costs. The latter will have to allocate increasing investments to energy in order to produce decreasing amounts of oil and gas from almost fully depleted reservoirs. Nevertheless, more research is required to fully represent the impact of alternative portfolios of energy sources on the total energy input to the economy (Fig. 10).

8. Conclusions

Many international organizations, think tanks, and research institutions have released recently unequivocal scenarios on energy's future prospects. The peak in global oil production is likely to happen in the next ten to fifteen years, and decisions made between then and now are likely to have large impacts on our quality of life in the coming decades.

Although most of the discussion has been focused on how much oil is left in the ground, the IPCC among others has stated that we are facing an even bigger problem with global warming. While a larger global URR may, on one hand, allow the economy to grow and to have us more prepared for the upcoming energy transition, on the other hand, it would both allow our economy to expand its rate of fossil fuel consumption and delay North America's transition to alternative sources of lower GHG producing energy, thereby increasing the flow of emissions produced. In addition, this depletion of oil reserves is accompanied by a decline in EROI, indicating an even steeper drop off in the amount of energy oil can deliver to society.

The authors analyzed two cases of global ultimate recoverable oil reserves: 2.2 and 3 trillion barrels, a low and medium estimate within current research. Three sets of policy directions were chosen: Business As Usual (Market Based), Maximum Push for Renewables, and Low Carbon Emissions. Without restrictions on emissions, as in the Market Based scenarios, coal becomes the dominant energy source and substitutes for oil in the longer term. In all of the simulations, government taxes are expected to rise to service increasing debt and keep foreign capital at 30% of national investment. If US policymakers are able to implement the necessary polices, such as a 20% RPS by 2020 and increased CAFE Standards, along with increased energy conservation, we may have the opportunity to smooth the medium to longer-term impacts of a global peak in oil production and an increased reliance on coal. There is no silver bullet which will solve our energy needs, but there is a solution that lies in developing a good strong renewable energy system that minimizes GHG emissions along with a program to reduce demand. It will require a number of effective policies and actions.

The impact of the energy transition beyond oil can have relevant impacts on both households and the industry, as shown by the Cheese Slicer conceptual model that helps understand the dynamics of consumption and investment allocation. 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. Nevertheless more research is required to fully represent the impact of alternative portfolios of energy sources on the total energy input to the economy.

The authors identify several directions for future research. The most immediate is to expand the model to include additional countries and model the energy trading interactions between them, in addition to Mexico and Canada already implemented in the model currently. This will imply the study of additional energy technologies and the endogenous calculation of EROI for other energy sources. The expansion of the model to create a game interface is being considered to help users understand how some of the key feedback loops in the real world interact with each other, and what policies and actions have the best hope of shaping an acceptable future.

References

American Council on Renewable Energy (ACORE), 2007. The outlook on renewable energy in America.

Bassi, A.M., 2008. Modeling US energy policy with Threshold 21, VDM Verlag Dr. Mueller e.K.

Brown, S., 2003. U.S. natural gas markets in turmoil, USAEE: Dialogue, p. 12.

Bunn, D.W., Larsen, E.R. (Eds.), 1997. Systems Modelling for Energy Policy. Wiley, Chichester.

Campbell, C.J., Laherrère, J.H., 1998. The end of cheap oil, Scientific American, March, pp. 80–85.

Centre National de Recherche Scientifique CNRS Grenoble, 2006. The POLES model: POLES state of the art. Laboratoire d'Economie de la Production et de l'Intégration Internationale, LEPII-EPE.

Cleveland, C.J., 1992. Energy quality and energy surplus in the extraction of fossil fuels in the U.S. Ecological Economics 6, 139–162.

Cleveland, C.J., 2005. Net energy from the extraction of oil and gas in the United States. Energy 30 (5), 769–782.

Cleveland, C.J., et al., 1984. Energy and the U.S. Economy: a Biophysical Perspective. Science 225 (5), 890–897.

Deffeyes, K.S., Hill, Wang, 2005. Beyond oil— the view from Hubbert's Peak, New York.

Drud, A., Grais, W., Pyatt, G., 1986. Macroeconomic modeling based on social accounting principles. Journal of Policy Modeling 8 (1).

Energy Information Administration (EIA), U.S. Department of Energy, 2003. The national energy modeling system: an overview 2003.

Energy Information Administration (EIA), U.S. Department of Energy, 2007a. Annual Energy Outlook 2007 (AEO).

Energy Information Administration (EIA), U.S. Department of Energy, 2007b. Annual Energy Review 2006 (AER).

Fiddaman, T.S., 1997. Feedback Complexity in Integrated Climate–Economy Models. Doctoral Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Fishbone, L.G., Giesen, G., Goldstein, G., Hymmen, H.A., Stocks, K.J., Vos, H., Wilde, D., Zöcher, R., Balzer, C., Abilock, H., 1983. User's guide for MARKAL. IEA Energy Technology Systems Analysis Programme.

Gately, D., 2004. OPEC's incentives for faster output growth. IAEE: The Energy Journal, pp. 75–96.

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005

Gleick, P.H., Cooley, H., Katz, D., Lee, E., 2006. World's Water 2006–2007: The Biennial Report on Freshwater Resources (World's Water). Island Press.

Hall, C.A.S., Cleveland, C.J., Kaufmann, R., 1986. Energy and Resource Quality The Ecology of the Economic Process. John Wiley and Sons (Wiley Interscience New York).

Heinberg, R., 2003. Party's Over: Oil, War, and the Fate of Industrial Societies. New Society Publishers.

Hubbert, M.K., 1974. On The Nature of Growth. Hearing on the National Energy Conservation Policy Act.

Intergovernmental Panel on Climate Change (IPCC), 2007a. IPCC Fourth Assessment Report: Climate Change 2007, Working Group I Report: The Physical Science Basis.

Intergovernmental Panel on Climate Change (IPCC), 2007b. IPCC Fourth Assessment Report: Climate Change 2007, Working Group II Report: Impacts, Adaptation and Vulnerability.

Intergovernmental Panel on Climate Change (IPCC), 2007c. IPCC Fourth Assessment Report: Climate Change 2007, Working Group III Report: Mitigation of Climate Change.

International Energy Agency (IEA), 2007. Medium-Term Oil Market Report—July 2007, Paris.

Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL family of models. IEA Energy Technology Systems Analysis Programme.

Messner, S., Strubegger, M., 1995. User's guide for MESSAGE III. International Institute for Applied Systems Analysis IIASA, Laxenburg, Austria.

Messner, S., Golodnikov, A., Gritsevskii, A., 1996. A stochastic version of the dynamic linear programming model MESSAGE III. Energy 21, 775–784.

Morecroft, J., 1983. System dynamics: portraying bounded rationality. Omeqa 11, 131–142.

National Technical University of Athens NTUA, 2005. The PRIMES Energy System Model: Summary Description, Athens.

National Technical University of Athens NTUA, 2006a. GEM-E3 model manual. Institute of Computers and Communications Systems.

National Technical University of Athens NTUA, 2006b. General Equilibrium Model for Economy–Energy–Environment, Model Manual, Athens.

Nordhaus, W.D., 1973. The allocation of energy resources. Brookings Papers on Economic Activity 3, 529–570.

Odum, H.T., 1971. Environment, Power and Society. Wiley–Interscience New York, New York.

Odum, H.T., 1983. Systems Ecology: An Introduction. Wiley Interscience, New York.

Pimentel, D. (Ed.), 2008. Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks. Springer.

Pyatt, G., 1991. SAMs, the SNA and National Accounting Capabilities. Review of Income and Wealth, Series 37, No. 2 p. 177–198.

Simon, H., 1979. Rational decisionmaking in business organizations. Americun Economic Review 69, 493–513.

Sterman, J.D., 1981. The energy transition and the economy: a system dynamics approach, Ph.D. Thesis, MIT.

Sterman, J.D., Richardson, G.P., Davidsen, P.I., 1988. Modeling the estimation of petroleum resources in the United States. Technological Forecasting and Social Change 33.

Strahan, D., 2007. Slippery slope, in The Guardian, October 3, 2007.

USDA, 2007. Agricultural Projections to 2016.

USGS, 1976. Principles of the mineral resource classification system of the U.S. Bureau of Mines and U.S. Geological Survey. USGS Bulletin 1450-A. Washington, D.C.

USGS, 2000. World Petroleum Assessment 2000.

Please cite this article as: Bassi, A.M., et al., An integrated approach to energy prospects for North America and the rest of the world, Energy Economics (2009), doi:10.1016/j.eneco.2009.04.005