November, 2010

Understanding the impact of policy on the energy system, the economy and the environment

Introduction

This report summarizes Ventana's work partially funded by the Department of Energy, Office of Science to develop realistic simulation models to compute the impact of R&D budgets and broader policies on economic growth and the environment. The paper briefly describes the goals of the work, the results so far, and the proposed completion of the work as a platform enabling robust anticipation of the impact of financial, R&D, investment and other policies on the health of the energy, environment, and economic systems.

The groundwork: E3

In the past few years we have developed the prototype working energy, environment, economy model E3. In this subsection we review its main features and present some results that offer insights to the potential benefits of the full-fledged model.

i. Overview

The three sections of the E3 model are:

Economy

The fundamental units of the model economy are firms, which are characterized by an array of ten elementary traits. Six determine a firm's personality: the propensity to change spontaneously or deliberately, and copy others; the degree to which personality or policy attributes are copied; and environmental sensitivity. Four additional traits determine operational efficiency: energy and labor; efficiency in using primary materials; and effectiveness of output. These are assigned on a firm's birth, at this preliminary stage from semi-empirical distributions designed to induce desired collective effects.

These basic attributes evolve through a firm's life deliberately or spontaneously, in response to perceived signals from the environment and a firm's current internal state. Synthetic features further characterize firms – e.g. their workforce size, volume of capital, or portion of newly built capital committed to any one energy source – molded by interactions with the environment.

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At the present stage of implementation, in order to maintain a controllable number of agents, firms are more akin to vertical sectors than conventional businesses: they produce output both as products for delivery in the market and as capital for their own use. This output embeds characteristics that mirror the firms' respective attributes: essentially instantaneous for products, integrated over time for capital that takes longer to complete.

The market rewards or punishes the individual firms depending on their overall perceived quality, efficiency, prevalence in market share, and environmental friendliness relative to the ambient mood – which is endogenous, reflecting macroscopic averages across the model. Firms that are well perceived in the context of their contemporary environment see their revenues rise and their credit-worthiness go up. The firms respond to good fortune by deliberate expansion, boosting their capital, labor force and production output; or, on the contrary, by deliberate shrinkage in size and output, as well as by spontaneous changes under the pressures of perceived failure. Occasionally firms die, picked randomly with a probability that grows as a firm's performance rank falls, tuned semi-empirically to attain average firm lifetimes in accord with published data.

Accounting and resource management mechanisms are implemented in the model, invoked by each individual firm at each time step (currently one year). These rational mechanisms comprise assessing a firm's relative performance, its stock of capital with its embedded properties, the size of its labor force, its personality and efficiency traits, as well as the availability of resources in the environment. In particular, the resources which are currently monitored in the model are cash, energy, labor, and primary materials. On the basis of these processes each firm individually both sets immediate goals (next time-step) and revises long-term targets for production and capital.

A rudimentary banking system is implemented which monitors cash flows across the economy and for each individual firm, and includes some banking policy levers that regulate interest rates, can somewhat control inflation, or trigger the injection of new cash to compensate for growth in the size of the economy. Stocks of used capital discarded by defunct firms are maintained, which are recycled alongside new capital depending on demand. A population model is implemented, and stocks of unemployed workforce are maintained. An energy sector (discussed further below) delivers various sources of energy and sets prices compatible with market conditions. Each firm at each time-step bids for the resources it needs (cash in the form of loans, energy, labor, and materials which are other firm's products). Overall resource availability and a firm's effectiveness determine the degree to which the desired resources at each time-step are secured. Constraints in resource availability are accounted for by mechanisms described above, resulting in necessary adjustments in the long-term forecasts and the targets that firms set for themselves.

Similar processes are implemented for startup firms, which begin as candidates assessed on their promise as reflected by their attributes and overall availability of resources. Candidate startups must secure a threshold of desired resources vis-à-vis their target capital. If they pass they are promoted to startup firms, entering a stage of exclusively building capital. On attaining a fraction of their target for capital, determined probabilistically, they start production and are granted a grace period over which they are assessed leniently relative to mature firms. On reaching their initial capital quotas, or exceeding a reasonable amount of time allocated for their buildup, they begin to be treated as mature firms.

An aggregate household sector is also implemented, currently characterized by passive attributes that mirror macroscopically the part of the economy comprised by the firms. The households are funded by the business sector via labor, build their own stock tuned semi-empirically to account for housing and durable goods, consume energy in proportion to their stocks of capital, and are the primary consumers of the firm products. The rates at which households consume products and energy or build capital in the model are subject to availability constraints similar to the firms.

Energy

The energy sector is currently modeled semi-macroscopically, supplying four sources of energy: coal, oil and gas combined, hydroelectric and nuclear energy combined, and all other renewable sources of energy collectively. Stocks of the natural reserves of the fossil fuels consistent with available data are maintained, and their depletion as a function of the consumption rates in the model economy is monitored. Stocks of capital are maintained for the extraction or generation of each energy source. The rates of energy production and capital construction adjust in response to energy demand. An empirical model accounts for the effect of the depletion of non-renewable sources on the efficiency of their extraction.

Tax policy scenarios are implemented, including carbon taxes linked to the level of emissions. A pricing model accounts for effects of depletion, demand pressures, technological improvements, and taxation.

Environment

Carbon emissions from the consumption of fossil fuels in the economy sector are monitored, and their concentrations are estimated in the atmosphere, the oceans, and the biosphere. Impacts on the climate are estimated as the net influx of heat in the atmosphere and the oceans. An abstract damage effect emulates economic impacts of accumulated damages to the environment. As this component is largely unchanged relative to the FREE model, the reader is referred to [1] for further details.

ii. Calibration and results

The current model is intended to reproduce an economy in the ballpark of that of the US in some important respects. In achieving this, we have substantiated the proposition that a rigorous calibration to empirical data is feasible.

The simulations shown in this document cover the period from 1960 to 2200 in yearly time steps. We use US data from 1960 to 1995 or 2000 [3] that overlap with the simulations, and tune the model for reasonable agreement in population, GDP, and total energy consumption (Figures 1, 2). A host of other model variables are initialized for 1960, the start year, using US data from various sources whenever available; e.g. capital embodied in the overall economy, embodied energy capital by source, energy production rates by source (classified as in the model), etc.

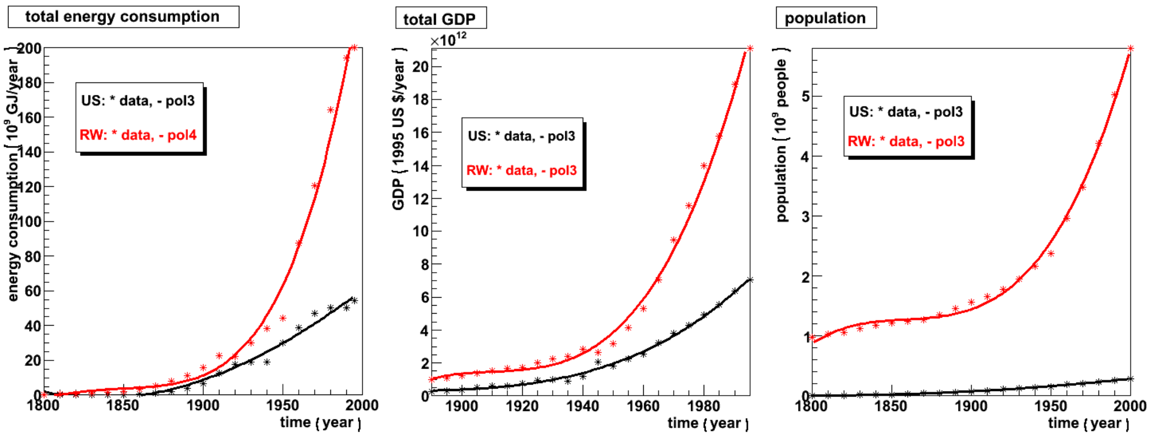

Figure 1 From left to right: total energy consumption, total GDP, and population; for the US in black, for the rest of the world combined in red. The asterisks depict data points [3], while the curves show best fits using third or fourth order polynomials, as indicated in the figures.

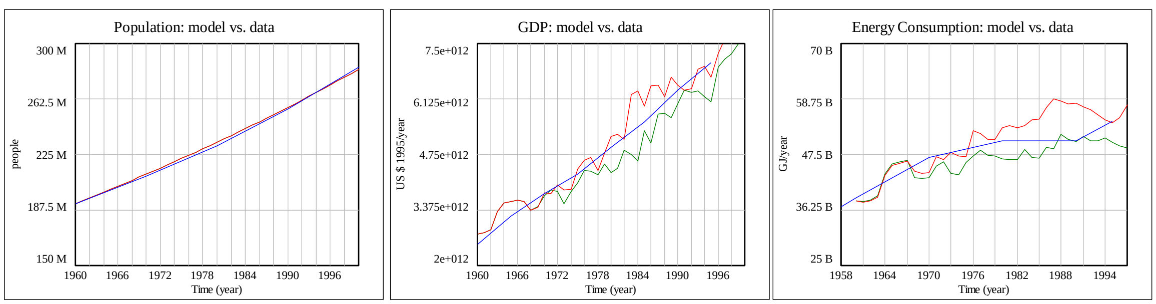

Figure 2 From left to right: US population, US GDP, and total US energy consumption; fits from Figure 1 (in blue) shown against two typical model simulations (in red and green) with somewhat different initialization assumptions for the embodied energy capital. It is pointed out that many variables in the model are assigned stochastically (e.g. attribute assignments to startup firms) so that individual simulations differ from one another even with identical initialization assumptions.

While we eventually will include all the regional world economies that interact with the US, currently we can accommodate a single economy. In order to carry out this exercise we therefore had modeled the US as an isolated, self-contained economy. Nevertheless, to maintain the integrity of the model, we had to preserve the world dependence of certain aspects in the model which are inherently global – e.g. the depletion rate of the natural reserves of fossil fuels, the consequent demand pressures and effects on price, carbon concentration in the environment etc, that depend on world energy consumption. This required extrapolating from the aggregate consumption generated by the model for the US to its world counterpart, using scaling estimators derived from existing data (Figure 3).

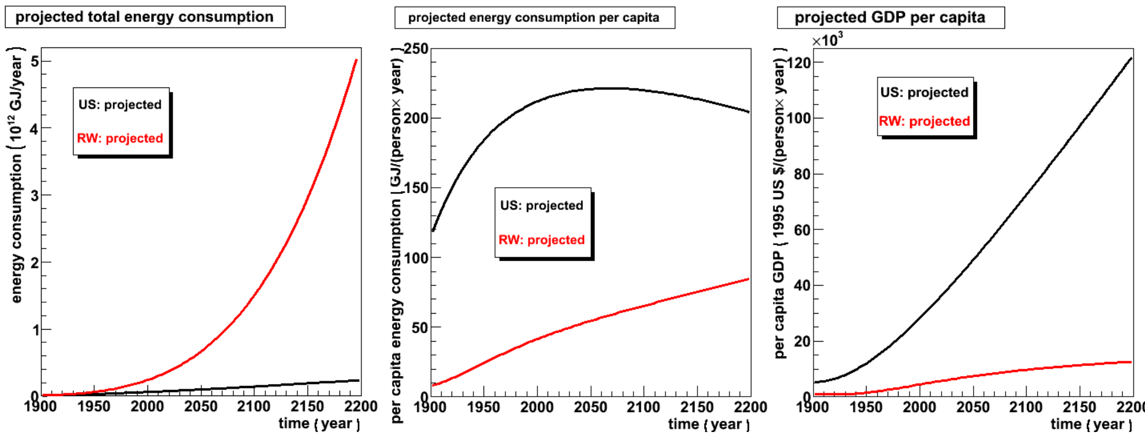

Figure 3 From left to right: total energy consumption, energy consumption per capita, and GDP per capita; in black for the US, in red for the rest of the world combined. The curves are obtained using the fits of Figure 1, projected beyond the range of the datasets up to 2200. We use these curves for estimating scaling factors between US energy consumption and its world counterpart, to estimate in the model the depletion rate of fossil fuel reserves and carbon concentrations from emissions in the environment, as discussed in the text.

In the rest of this section we show simulation results probing the effects of R&D on the evolution of the US energy consumption profile, GDP, and carbon emissions. The particular examples we chose are meant only as illustrations of the uses of our model to inform policy. Our baseline case includes neither energy taxes nor R&D explicitly. In addition, we consider two scenarios: in the first, fossil fuels are increasingly penalized by moderate taxes as concentrations of carbon in the environment rise, with the proceeds funding exclusively R&D of exotic renewable sources; in the second we make the same assumptions as in the first but in addition have firms spending a flat 2% of their revenues individually on generic (not explicitly energy related) R&D (Figures 4-6).

All three scenarios are characterized by a rather stable per capita growth rate converging in the long run to an average between 1.6-1.9% per year, in agreement with historical data of wealthy economies, with increasing levels of R&D inducing marginally faster growth. However, the impact of R&D on energy consumption is significant (Figure 4). In the baseline scenario the consumption of oil and gas peak near 2050, subsequently declining relatively rapidly as the effects of depletion set on. As the use of oil and gas declines, coal, hydro and nuclear energy move in to replace their share. The effect of only tax-funded R&D is marginal on the consumption pattern of oil and gas, but important in altogether lowering energy consumption, as well as shifting strength away from carbon to hydro and nuclear energy primarily, and to the renewable sources secondarily. Perhaps an unintuitive result is that the use of carbon taxes in our model to fund R&D on renewable sources, in the long term results in considerably lower rather than higher prices for oil and gas – as well as lower prices for the renewable sources. This is the combined effect of two synergistic processes: First, R&D on renewable sources induces faster improvement of related technologies. By virtue of this, renewable sources gain attractiveness – because capital that consumes as well as produces them becomes more efficient – and a shift of the economy toward them begins earlier than in the absence of R&D. Second, as a result of this shift, demand on oil and gas is reduced. This in turn slows down the rate of depletion of oil and gas, which in the model is the main driver of price hikes in the era of severely depleted reserves, keeping their prices lower.

The addition of firm- on top of tax-funded R&D in effect accelerates and amplifies the effects of only the latter, but with some intriguing variations. First, in the early period of dominance of the fossil fuels, investing individually in R&D induces the firms to be more energy intensive – as well as generate faster growth. This causes higher total energy consumption during that time, faster decline of the oil and gas reserves, and an earlier onset of the ensuing rapid decline of their use relative to the previous two scenarios (Figure 4). Subsequently however, as other energy sources begin to replace oil and gas, total energy consumption plateaus and begins to decline, while coal consumption is suppressed and the renewable sources are set on course to rapidly dominate.

The pattern of overall energy consumption in the three examined scenarios is pretty much mirrored by the accumulated energy-related carbon emissions to the environment (Figure 5).

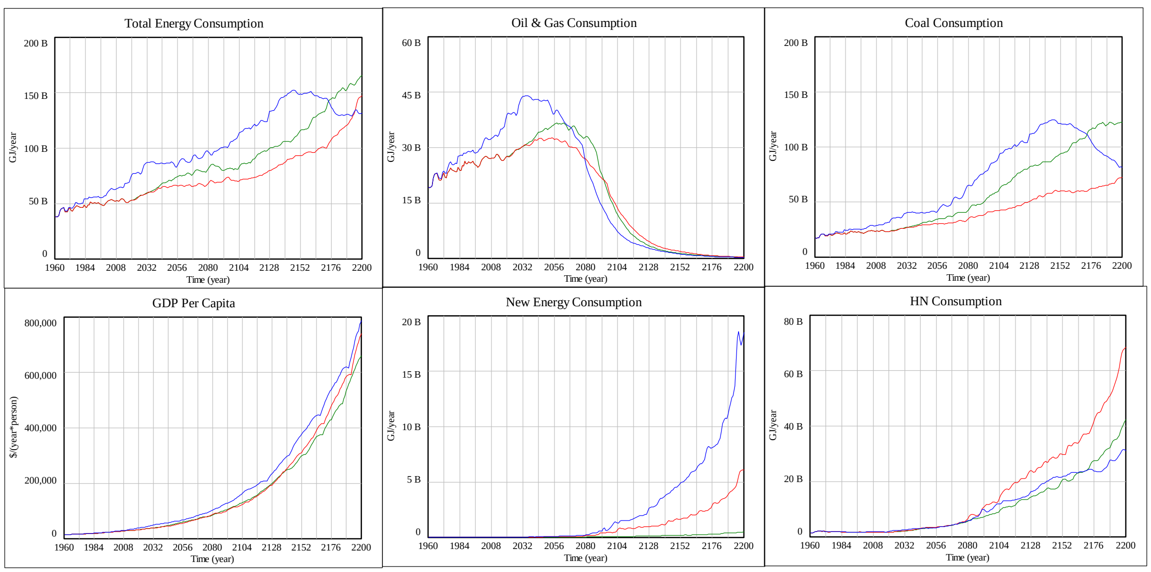

Figure 4 Clockwise from top left: total, oil and gas, coal, hydro and nuclear, other renewable annual US energy consumption; bottom left: GDP per capita in 1995 $. Simulations: no carbon taxes or R&D (green); modest carbon taxes funding R&D of new renewable sources (red); as before plus firm-funded R&D at 2% of revenues (blue). In all three scenarios oil and gas use peaks around 2050, thereafter falling rapidly as the effects of depletion set on. The impact of carbon taxes or R&D is modest on GDP, but significant on the US energy consumption profile.

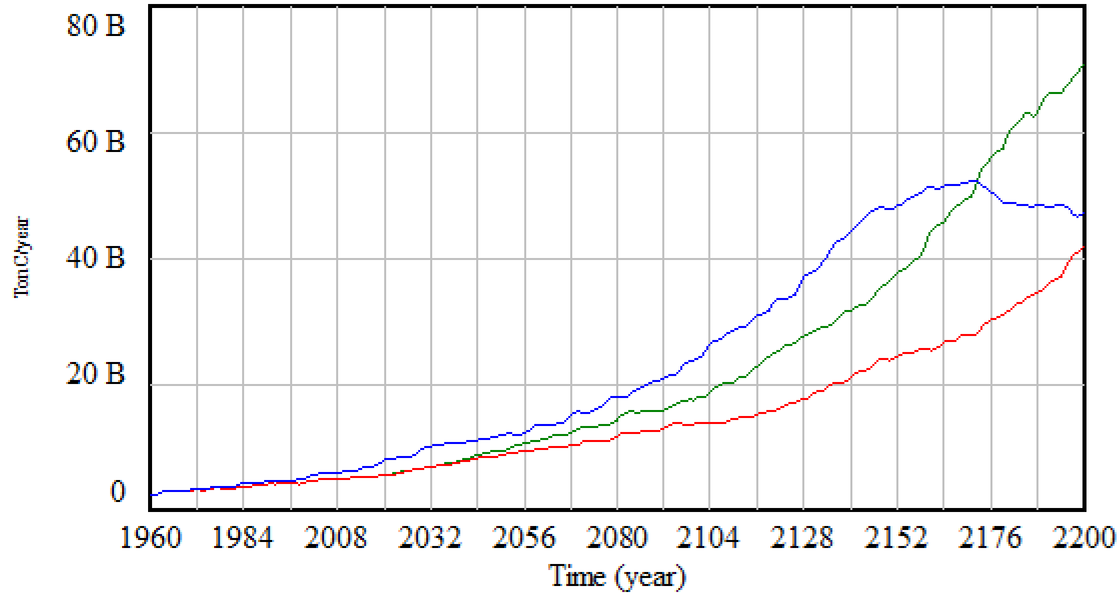

Figure 5 Annual world energy carbon emissions corresponding to the scenarios of Figure 4.

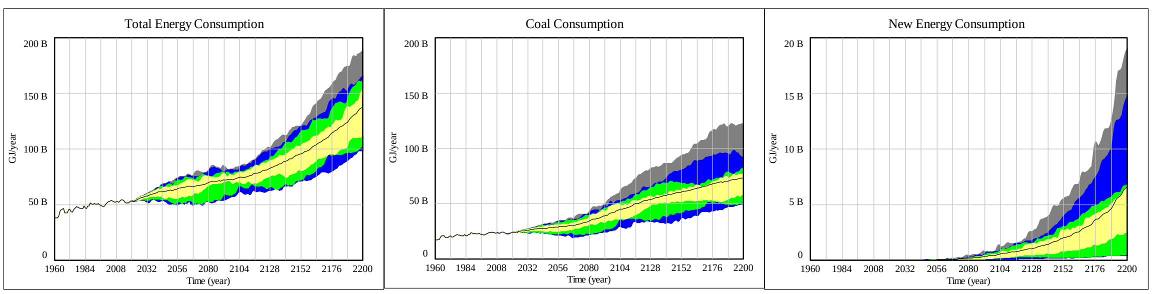

Figure 6 Dependence of the annual US total energy, coal, and exotic renewable consumption on carbon taxes, varied from zero to double the level of the run in red of Figure 3. Coupled with automated algorithms that optimize policy parameters to achieve desired objectives, sensitivity studies such as these can be valuable in informing policy making.

References

[1] T. Fiddaman, *Dynamics of climate policy*, System Dynamics Review **23**, 21-34 (2007).
[2] D.W. Peterson, unpublished.
[3] HYDE data repository, Netherlands Environmental Assessment Agency (http://www.mnp.nl/hyde/download/)