ENERGY MARKET CONSEQUENCES
OF AN EMERGING U.S. CARBON MANAGEMENT POLICY

Innovation, Renewable Energy, and Macroeconomic Growth

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About the Study: Energy Market Consequences of an Emerging U.S. Carbon Management Policy

Emerging energy and climate policies in the United States are accelerating the pace of technological changes and prompting calls for alternative energy and stricter energy efficiency measures. These trends raise questions about the future demand for fossil fuels, such that some energy-producing nations are reluctant to invest heavily in the expansion of production capacity. The abundance of shale gas resources in North America could allow the United States to utilize more gas in its energy mix as a means of enhancing energy security and reducing CO2 emissions. However, this will only occur if U.S. policies promote and allow the benefits provided by natural gas to be realized. To examine these issues and changing trends in the U.S. energy and climate policy, the Baker Institute organized a major study investigating the North American and global oil and natural gas market consequences of emerging U.S. policies to regulate greenhouse gas emissions, as well as the potential role of alternative energy in the U.S. economy.

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Abstract

Many studies assume that the optimal size of research and development (R&D) in the energy sector is five to 10 times the current level. Is the energy sector under-investing in R&D? What would be the effects of subsidies to R&D in renewable energy on macroeconomic growth? There is an extensive ongoing policy discussion in the United States about innovations in the "green economy" and their potential to act as a new engine of economic growth. As the new administration devotes substantial resources to production and investment subsidies in the renewable energy and biofuels sector, it is important to evaluate the validity of such a strategy. In our model, energy is needed in order to produce the economy's consumption good. We find that the economy goes through three distinct regimes. Initially, production uses only fossil fuel, and investment takes place in order to improve the efficiency of supplying fossil fuel. In the medium to long run, the price of fossil fuel inevitably increases, and the economy makes a transition to a renewable energy regime. Finally, in the very long run, a limit is reached after which renewable energy is produced at the lowest possible cost. We calibrate the model and examine how the transition to renewable energy is affected by imposing taxes on fossil fuel energy or by imposing subsidies to renewable energy R&D.

1 Introduction

Many studies assume that the optimal size of research and development (R&D) in the energy sector is five to 10 times the current level. Is the energy sector under-investing in R&D? What would be the effects of subsidies to R&D in renewable energy on macroeconomic growth? Currently there is an extensive ongoing policy discussion in the United States about innovations in the green economy and their potential to act as a new engine of economic growth. With substantial resources devoted to production and investment subsidies in the renewable sector, it is important to have such policies evaluated. This, in turn, requires building models in which there is a clear link between innovation in renewable energy, government subsidies, and gross domestic product (GDP) growth. This paper attempts to provide such a model.

There are some theoretical arguments, as well as certain empirical indications, that R&D in the energy sector is low in relative terms. The strongest theoretical reasoning can be developed around the notion of "creative destruction." Innovation often results in old technologies becoming obsolete. In the energy sector, this is exacerbated by regulatory uncertainty. Large fixed costs and long time horizons also mean that firms in the industry have a lot at stake when choosing investment plans. Profit maximization therefore might lead energy companies to be reluctant to invest substantial resources into R&D in new technologies. This reluctance to adopt revolutionary changes, as opposed to investing in improvements to the existing structure, might indeed lead to a market failure, resulting in a discrepancy between profit maximization and a socially efficient level of R&D. This, in turn, might imply the need for government subsidies or related measures, such as taxing fossil fuels, that could induce additional R&D in renewable energy and, thus, speed up the transition towards a renewable energy based economy. Authors such as economist Bjorn Lomborg have suggested that the best way forward is to subsidize research in renewable energy, so that green-energy technologies become cheaper over time (Charles, 2010).

Data show a sharp decline in energy R&D that has not fully recovered. In the early 1980s, energy companies invested more than drug companies in R&D. However, the trend turned sharply negative, and R&D has not fully returned to its late 1970s and early 1980s levels. According to the Belfer Center at Harvard University (Gallagher and Anadon, 2010), total government energy technology research, development, and demonstration (RD&D) fell from over $6 billion per year between 1978 and 1981 to a low of $1.4 billion in 1998 (in 2005 dollars). It then slowly rose but did not reach $3 billion again until 2009. The fall in government RD&D for renewable energy was even steeper from peak to trough, falling nearly 90 percent from 1979 to 1990. In 2005 dollars, the government spent at least $1.5 billion/year between 1978 and 1981, but less than $500 million/year from 1984 through 2006.

The same general trajectory has been seen with private R&D. According to data from the Global Energy Technology Strategy Program and Pacific Northwest National Laboratory, private energy R&D spending basically mirrored the trajectory and magnitude of government R&D energy spending through 2003 (Runci and Dooley, 2007. Even together, private and public energy R&D have accounted for a relatively small portion of total R&D spending, reaching a peak of about 10 percent around 1980 and falling to only about 2-3 percent by the late 1990s.

Recently, government investments have increased alternative energy R&D, and the private sector also seems more willing to invest in clean technology projects. The 2009 American Recovery and Reinvestment Act (ARRA), often referred to as the stimulus package, provided over $6 billion in RD&D spending; the government is spending nearly $900 million on renewables in 2009 in addition to the ARRA. As of September 2010, the ARRA made available $31.2 billion to the U.S. Department of Energy (DOE), although much of the money was slated for issues like deployment of technology or weatherization that have no R&D component (Recovery.gov, 2010). In the private sector, venture capital funding has been flooding into the "green tech" industry. By the third quarter of 2009, 27 percent of venture capital went into "green tech," more than biotech or software ventures received (LaMonica, 2009). This compares with less than five percent through much of the 1990s and early 2000s (Runci and Dooley, 2007).

Still, there is no legislated plan for long-term government commitment to R&D spending. President Barack Obama as a candidate proposed spending $150 billion over 10 years, focusing on three areas – basic research, technology demonstration, and aggressive commercial deployment and clean market creation – but it has not been implemented into law (Obama for America, 2008). More recently, President Obama has proposed increasing and permanently extending a popular tax credit for businesses' research expenses.[1] This credit has existed in some form since 1981 and has generally received bipartisan support.

As Obama's plan shows, government support can come at many points along the value chain, from initial research to assistance with commercialization. Some experts and organizations, including the Intergovernmental Panel on Climate Change (IPCC) and the DOE, have actually dubbed this process RDD&D, with the extra "Ds" usually standing for demonstration and deployment (IPCC, 2007; DOE, 2009). Government support can also come before this process in the form of basic science research without clear or direct commercial applications – compared with the applied research implied by R&D – funded by the government through entities such as the National Science Foundation. On the other hand, many policies can help to support demand for renewable technologies once they are commercially deployed by subsidizing or mandating installation or production. Examples of such policies in the United States include the production tax credit granted per kilowatt-hour generated, and state-level renewable portfolio standards that usually mandate a certain percentage of electricity be generated from renewable sources. In Europe, a popular incentive designed to increase renewable generation is known as a feed-in tariff, which requires utilities to pay renewable operators a high rate for their electricity, a cost that is then borne by consumers through higher electricity rates.

This paper is most directly relevant to traditional R&D spending or subsidization. It is less apt at modeling the impact of steps taken before and after traditional R&D such as basic science research and investment in demonstration plants. However, the real-world policy most similar to the subsidy discussed in the paper, the R&D tax credit, which reduces the tax burden of firms that invest in R&D, can at times affect basic research and construction of first-of-a-kind plants. An R&D tax credit could impact basic science research if a firm

[1] The White House, *Expanded, Simplified, and Permanent Research and Experimentation Tax Credit*, Fact Sheet, September 8, 2010, http://www.whitehouse.gov/sites/default/files/fact_sheet_re-credit_9-8-10.pdf.

decided to invest in such research, but due to the limited time frame of patents and the issue of creative destruction mentioned previously, firms likely under-invest in basic scientific research from a social point of view. A firm could also choose to invest in R&D in related technologies that could reduce the cost of overall installation, such as a cheaper inverter for a solar panel. Nevertheless, government policies for demonstration and deployment are most commonly in the form of direct grants or loan guarantees that reduce the cost of capital and overcome the barrier of receiving financing from banks weary of betting on unproven technologies.

Others in the private sector and think tanks are now calling for large increases in government support for energy RDD&D, which is sometimes collectively referred to as energy innovation spending. Recently, the American Energy Innovation Council (AEIC), whose members include prominent business leaders such as Bill Gates, Jeff Immelt and Norman Augustine, released a report that calls on the federal government to spend $16 billion/year on clean energy innovation (AEIC 2010). Other organizations, including Google.org, and the Breakthrough Institute, a think tank, have also pushed for around $15 billion/year of federal funds for a variety of programs to promote clean energy including increased R&D spending (Jenkins, 2009). Now that cap-and-trade failed and looks dead until 2013 at the earliest, these organizations are looking to R&D spending as a major fallback piece of U.S. energy policy. This paper will try to assess the relative merits of these policies in terms of economic growth, recognizing that economic growth should not be the sole criterion of policy-making, and that environmental and security considerations should be taken into account.

Supporters of increased government R&D spending use a variety of arguments for how it would increase economic growth. Some speak of the aforementioned "creative destruction" argument that private maximizing firms could under-invest in R&D from a social perspective because they are reluctant to take risks, given the large fixed costs and long time horizons. The implications of this argument would be that it is preferable for the United States to subsidize R & D for alternative energy rather than subsidize renewable energy production, as is currently the case, because subsidies on R&D more directly address the market failure of low R&D investment that the policy is attempting to redress. Subsidizing renewable energy production can create other energy pricing and energy use market distortions (see Hartley Wind paper) while at the same time still failing to provide adequate incentives for optimum levels of investment in R&D.

A separate and very widely articulated mechanism for how increased clean energy R&D investments can increase economic output – and one that appears to be getting the most political traction currently – posits that the United States needs to move first on clean energy before other countries establish their own industries. As Obama said in April 2009, "The nation that leads the world in creating a new clean energy economy will be the nation that leads the 21st century global economy."[2] Robert Atkinson, president of the Information Technology & Innovation Foundation, said during congressional testimony that nations that establish an early advantage in key industries can retain those advantages (such as economies-of-scale, learning-by-doing and supply chain efficiencies) at a lower cost than countries that move into the field later (Atkinson, 2010).

Those who look to the need for the U.S. to move more quickly to gain this first-mover advantage are primarily focused on China. China, which passed a landmark renewable energy law in 2007, initially pledged to spend $200 billion on renewable energy development over the next 15 years; however, the country recently pledged 5 trillion yuan (over $700 billion) in the next decade aimed at developing cleaner energy and reducing reliance on coal.[3] Additionally, many of the leading solar companies are already based in China.

The first-mover argument has significant deficiencies, however. Any good or process developed in one country can be relatively easily moved to another country or adopted by a rival producer in another country. Companies based in the United States can build manufacturing capacity outside of the country and sell products to consumers in other countries as well, leading to little, if any, domestic GDP increase. For instance, the leading manufacturer

[2] The White House, *President Obama Highlights Vision for Clean Energy Economy*, Fact Sheet, Office of the Press Secretary, April 22, 2009, http://www.whitehouse.gov/the_press_office/Clean-Energy-Economy-Fact-Sheet/.

[3] "10-Year Plan for Clean Energy," *Shanghai Daily*, July 21, 2010, http://www.china.org.cn/business/2010-07/21/content_20544793.html

of solar cells in 2009, First Solar, is a U.S. company that produces over 83 percent of its panels abroad (Osborne 2010). Additionally, high labor costs in the United States coupled with new sources of cheaper labor in Asia have steadily eroded manufacturing as a percentage of GDP, and it is difficult to imagine that the United States would be a consistent lowest-cost production center of clean energy technologies. Due to these problems, the effect of R&D on economic growth is not modeled using a game-theoretical framework necessary to approach the question from a first-mover perspective.

While this paper looks specifically at output as measured by GDP, some supporters of green technology R&D base their position on the creation of "green jobs." For instance, although the report was specifically related to Keynesian economic stimulus at the peak of the economic crisis, a 2008 University of Massachusetts study released by the liberal think tank Center for American Progress found that a $100 billion investment in green programs would create about two million jobs over two years, although the report was specifically related to Keynesian economic stimulus at the peak of the current economic crisis (Pollin et al., 2008).

The idea that technological advancements are a major or primary driver of economic growth is not a new one. During the Clinton administration, the Council of Economic Advisers issued a report that half or more of the increase in output was due to investment in R&D (CEA 1995). Examples include Kammen and Nemet (2005), who used the Clinton CEA data to argue that the economic benefit from a 5 to 10-fold increase in energy R&D spending over the then-current levels would repay the country in job creation and global economic leadership, building a vibrant, environmentally sustainable engine of new economic growth. In this vein, proponents cite numerous technologies that have originated from government-sponsored R&D programs (Alic et al., 2010).

Other organizations have described the reputed economic benefits of increased R&D expenditures. The Apollo Alliance (2004) suggests that a major investment in alternative energy technologies could add more than 3.5 million new jobs to America's economy, stimulate $1.4 trillion in new GDP, and pay for itself within 10 years. The AEIC points to what it sees as successes from the $30 billion/year in federal funds spent on the National Institutes of Health, which it claims has made America the leader of the pharmaceutical industry.

As a candidate, Obama argued that his $150 billion clean energy plan over 10 years would "create 5 million new green jobs, good jobs that cannot be outsourced." GDP and unemployment are usually connected by Okun's Law, which states that rising GDP tends to be correlated with falling unemployment, but they do not always move in perfect sync. The important factor would be "net jobs," or the increase in jobs in the renewable sector compared with the loss of jobs in the fossil fuels sector. In the long-run, the number of jobs in the two sectors would be determined by the number of people needed to produce a certain amount of energy from a fuel source, which can be called the "job intensity" of the fuel. A recent paper by Wei, Patadia and Kammen (2010) conducts a meta-analysis of previous studies; the authors try to analyze the job intensity of various fuels and concludes that renewables are somewhat more job intensive than fossil fuels. However, the job intensity for a particular fuel can change substantially over time; the output of an hour of a coal miner's labor in 2006, for instance, was about three times that of his labor in 1970 and over eight times that of the labor in 1950 (EIA, 2006). Since many renewable sources require no oversight except for occasional maintenance, it does not seem intuitive that renewables will permanently be more job intensive.

In practice, government subsidies for renewable energy may not have particularly desirable effects on economic activity and job creation, although specific details of the policies implemented affect the final results. A sober Universidad Rey Juan Carlos study (Álvarez et al., 2009) on the Spanish experience finds that a $36 billion total subsidy for renewable energy between the years 2000 and 2008 created an estimated 50,000 related jobs (mainly in construction, maintenance, operation, and administration). However, the study concludes that the implied average subsidy of €571,000 per job in renewable energy led to an estimated 9 jobs lost in the economy for every 4 created.[4] It is notable that the primary policy mechanism in Spain was a feed-in tariff, which guarantees that the prices consumers pay

[4] Lantz and Tegen (2009) identify some shortcomings in the Spanish study.

for electricity will be higher; this policy mechanism is very different from an R&D subsidy because it subsidizes the installation of technologies that are already commercially viable. Still, extra R&D expenditures should also increase energy costs if fuels are taxed to pay for the subsidy. Higher energy prices, taxes or debt can all reduce employment. Subsidies also could "absorb" capital away from other, perhaps more productive parts of the economy.

With over $2 trillion in annual sales worldwide, the energy industry is the largest on the planet. Thus, economic policies that affect the energy sector are likely to have global consequences. Yet, seldom are such policies studied and evaluated using the standard tools of macroeconomics: quantitative, dynamic general equilibrium modeling (Kydland and Prescott, 1982). For this paper, we build a model in which to study the technological progress of renewable energy as a potential engine of macroeconomic growth. We compute the equilibrium optimal path of investment in both the fossil fuel and the renewable energy sectors. Finally, we evaluate different policy scenarios regarding the imposition of taxes on the use of fossil fuel and the effect of government subsidies (financed by taxation) on the use and development of renewable energy.

Our basic model involves a growth model in continuous time. As Hartley and Medlock (2005) observe, energy is needed in order to produce the model economy's single consumption good. Energy can come from two sources: fossil fuel and a renewable source. The marginal resource cost of fossil fuel extraction increases with the total quantity of resources mined to date. At the same time, we assume that investments in mining technology or energy efficiency can reduce the unit cost of supplying fossil fuel. Turning to the renewable source, we explicitly model technological progress by assuming that, due to learning-by-doing, experience with using renewable energy lowers the unit cost of these energy sources.

There is some existing research on issues related to R&D and growth that develops models related to ours. Acemoglu et al. (2009) introduce a growth model that takes into consideration the environmental impact of operating "dirty" technologies that emit carbon dioxide. They then study the effects of policies that tax innovation and production in the "dirty" sectors. Their paper focuses on long run optimal growth and sustainability and abstracts from the endogenous evolution of R&D expenditures, which they assume to be constant. They find that subsidizing research in the "clean" sectors can speed up environmentally friendly innovation without resorting to carbon taxes and the corresponding slowdown in economic growth. Consequently, optimal behavior in their model implies an immediate increase in clean energy R&D, followed by a complete switch towards the exclusive use of clean inputs in production. Grimaud and Rouge (2008) study the effects of taxing polluting production factors and of subsidizing research on economic welfare. They find that optimal policy must reallocate research efforts towards "green" research. Rubio, García and Hueso (2009) study optimal growth in a model where there is value to environmental quality. They assume that "clean" technologies can be used in the economy if a part of the output is used in environmentally oriented R&D. They find that initially, there is a low level in "green R&D." However, as environmental quality declines, this activity becomes more profitable. Thus, the economy eventually adopts a path of increasing environmental quality.

In our model, we find that the economy goes through three distinct regimes. Initially, production uses only fossil fuel, and investment takes place in order to improve the efficiency of supplying fossil fuel. In the medium to long run, the price of fossil fuel inevitably increases, and the economy makes a transition to a renewable energy regime. Here, renewable energy is used and, at the same time, learning-by-doing reduces the cost of using the backstop technology. Finally, in the very long run, a limit is reached after which renewable energy is produced at the lowest possible cost.

We calibrate the model using data from the Energy Information Administration (EIA), the Survey of Energy Resources, and the GTAP 7 Data Base produced by the Center for Global Trade Analysis in the Department of Agricultural Economics at Purdue University. The last mentioned data source provides a consistent set of international accounts that also take energy flows into account.

We then examine how the transition to renewable energy is affected by imposing taxes on fossil fuel energy or by granting subsidies to renewable energy R&D.[5] Taxing fossil fuels

[5]An example of a related climate policy currently under discussion is the "American Clean Energy Leadership Act (ACELA)," which was reported out of the Senate Committee on Energy and Natural Resources

accelerates the rate of adoption of the renewable energy technology. However, a main finding of our analysis is that the elasticity of the adoption rate appears to be small. A tax as high as 20 percent accelerates the renewable technology adoption by about 11 years, while a more modest 2 percent tax accelerates the transition by only five years. Bill Gates has recently advocated for a tax rate of about 2 percent on energy that would be used to finance clean energy innovation, while the higher tax rates are more in line with proposals for cap-and-trade programs (Pontin, 2010). Given 2002-2006 base prices for fuels, a 20 percent tax on coal would be the equivalent to roughly a \$2.50/ton tax on carbon dioxide (CO_2), while a 20 percent tax on natural gas would be the equivalent to about a \$20/ton tax (Paltsev et al., 2007). Prices of carbon dioxide in Europe between mid-July and mid-August 2010 were between €13.5 and €14.5 /ton, a cost of about \$17.50/ton to \$19/ton at an exchange rate of \$1.30/€(PointCarbon 2010). The tax leads to less intensive fossil fuel use.

However, the resulting distortion creates a wedge between the equilibrium and the socially optimal level of investment. As a result, it can be shown that welfare in the economy declines with the size of the tax. In our model, subsidies for renewable energy investments also accelerate the rate of adoption of the renewable energy technology. Indeed, a renewable energy subsidy appears to be more effective than a tax on fossil fuels, with a 2 percent subsidy accelerating the introduction of the renewable energy regime by 16 years. Like the tax, the subsidy also leads to a distortion equivalent to its magnitude.

As a result of the renewable energy subsidy, fossil fuel reserves are used more intensively in the short run. This somewhat paradoxical conclusion can be explained as follows: Since the adoption of renewable fuel is accelerated as a result of the subsidy, the opportunity cost of fossil fuel use declines in the short run. Thus, while the subsidy on renewables leads to a faster transition towards renewable energy, it also implies a more intensive use of fossil fuel than what is socially optimal in the short run. While we do not model carbon dioxide or other emissions explicitly in our analysis, it is worth mentioning that this could imply a short

in June 2009 with the support of four Republicans (Geman 2009). It includes a variant of a "renewable energy standard" that mandates a certain percentage of electricity generation come from renewable sources and should lead to an expanded use of renewables.

run increase in greenhouse gas and other emissions associated with fossil fuel combustion.

The most similar policy tool to the R&D subsidy described in the paper is the R&D tax credit, which was first introduced in 1981 and has since been renewed 13 times. The credit expired at the end of 2009 and has not been renewed as of August 2010; this represents the only break since the year between July 1995 and June 1996.[6] It is quite complex, theoretically trying to support increasing levels of R&D research but including many caveats. According to the Government Accountability Office (GAO), the value of the net credit in 2005 was $6 billion, and it reduced the after-tax price of additional qualified research by an estimated 6.4 to 7.3 percent (GAO, 2009).

Currently, taxpayers can receive a tax credit equal to 20 percent of the amount paid to tax-exempt energy research consortiums.[7] Called the Energy Research Consortium Tax Credit, it was introduced in the 2005 Energy Policy Act (Hempling, 2008). Sen. John Kerry (D–MA) in August 2010 introduced the Clean Energy Technology Leadership Act of 2010, which extended the R&D tax credit retroactively for 2010 through 2012 and provide an extra 10 percent credit for certain advanced energy research expenditures.[8]

Our model does not distinguish between a subsidy enjoyed by a "private" or a "public" investor. The subsidy is actually quite similar in nature to the effect of direct government expenditures on R&D that have been getting some attention recently. Government grants will disproportionately go to organizations that currently spend their own money on R&D and have a proven track record. It that way, government is subsidizing their already existing work with its research grants.

The paper proceeds as follows. Section 2 presents some stylized facts, documenting the trends in R&D and in innovation in the energy sector. This involves studying (public) R&D dollars and patents, as well as "learning curves" derived from data from the renewable

[6] R&D Credit Coalition, Legislative History of R&D Credit Extensions, February 3, 2005, *http://www.investinamericasfuture.org/PDFs/233051.pdf.*

[7] "Energy Research Consortium Tax Credit," TechnologyTax.com, *http://www.technologytax.com/research-tax-credit/energy-research-credit/.*

[8] John Kerry – U.S. Senator for Massachusetts, "Kerry Bill Will Spur Clean Energy Production," news release, August 6, 2010, *http://kerry.senate.gov/press/release/?id=91FE4BAB-D8BF-4239-9DA4-815DAB5228EF.*

industry. Section 3 develops our main model. One of our main methodological contributions involves embedding R&D for fossil fuel production, fossil fuel depletion costs, and learning curves for renewable energy into a calibrated macroeconomic model of growth. We solve the corresponding optimal growth problem and discuss how the model is calibrated in order to perform numerical simulations. Finally, Section 4 studies the effects of different policy scenarios regarding the optimal rates of renewable technology adoption and the consequences for GDP growth. A brief conclusion follows.

2 Measuring Technological Progress

2.1 Patents

Although energy produced using renewable sources currently is more expensive than that produced by fossil fuel, the gap appears to be shrinking. Eventually, rising costs of fossil fuel and falling costs of renewable energy will lead to a transition to a predominantly renewable energy regime. Studying the determinants of when this parity in energy costs will occur, and especially the possible effects of policy on the transition, is one of the main goals of our paper.

In order to evaluate the effects of policy, it is important to understand the rate of technological progress in renewable energy in the presence of, as well as in the absence of government policy. To begin with, how can one measure technological progress in the renewable energy sector? One approach involves counting the number of new patents filed in the industry.[9] To measure progress, however, each patent needs to be weighted by the importance of the innovation it represents. Since each submitted patent contains citations to earlier related patents, one measure of the extent of innovation stimulated by a patent is the number of times it is subsequently cited. A simple procedure for measuring progress, therefore, is to count the number of patents that have been cited a minimum of three times. Another measure only counts patents that have been renewed upon expiration, since renewal is another

[9] See, for example, Popp (2002).

signal of the patent's value.

Figures 1 and 2 plot data from 1976 to 2009 on public R&D and patents for wind energy that have been renewed and cited at least three times. Figures 3 and 4 plot the corresponding data for solar energy.[10]

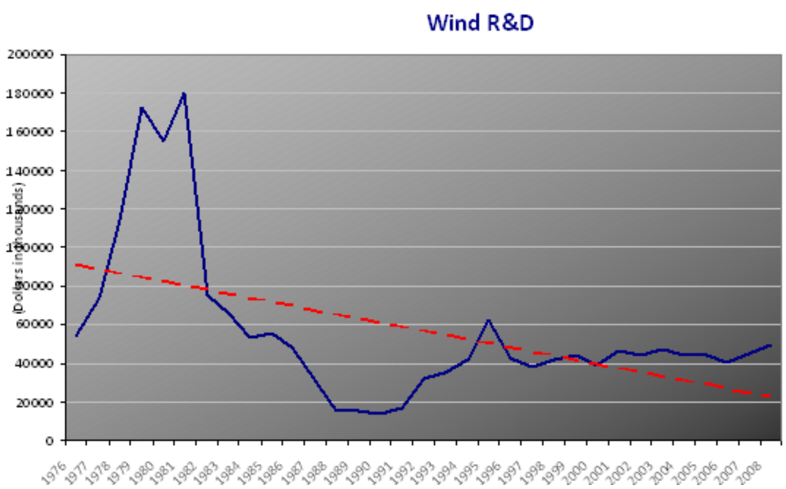

Figure 1: Wind R&D expenditure

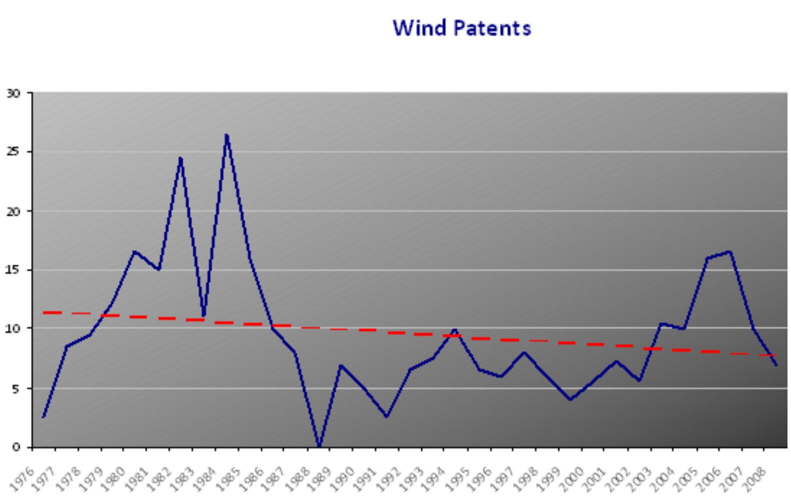

Figure 2: Wind patents

[10] Public R&D (in 2008 $) from the DOE. Patent data from the US Patent Office. Solar includes PV and thermal. Note that the number of cited patents inevitably declines towards the end of the sample period, as the newest patents have fewer opportunities to be cited.

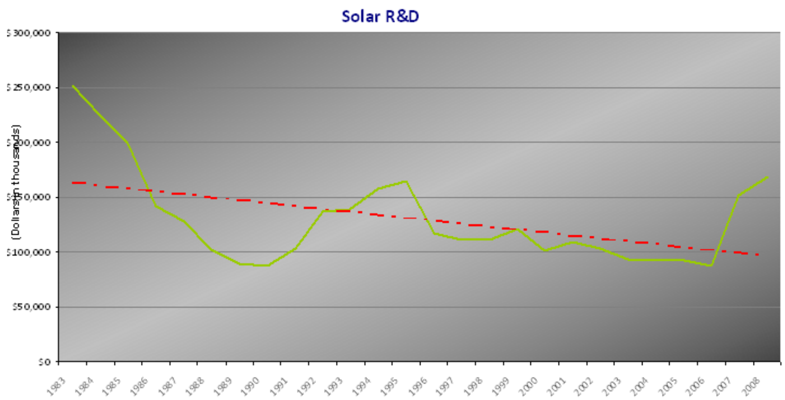

Figure 3: Solar R&D expenditure

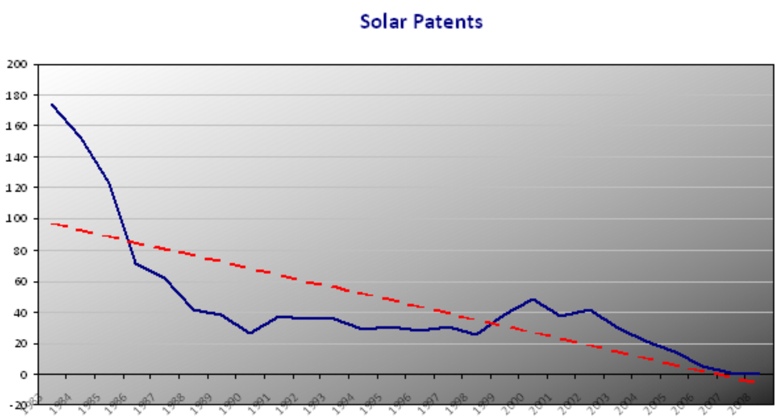

Figure 4: Solar patents

These graphs document non-increasing trends in both public R&D expenditure and innovation, as measured by patents, in both solar and wind energy. At least two explanations can be given for these trends. Several authors have pointed to decreased energy prices and low R&D budgets following the end of the oil crisis in the 1970s. This interpretation can find a theoretical justification in the literature on endogenous growth and, more specifically, the problem of "*creative destruction*." This argument goes as follows: New technologies often result in old ones becoming obsolete. Given the large fixed costs and the regulatory uncertainty that are prevalent in the energy sector, private profit maximization might lead energy companies to be particularly reluctant to invest substantial resources in renewable energy R&D. This reluctance to risk abandoning existing technologies might indeed lead to a market failure, resulting in a discrepancy between the profit maximizing and the socially efficient level of R&D. This, in turn, might imply the need for government policies that could induce additional R&D in renewable energy.

There is, however, another possibility. Declining levels of innovation (patents) might be the result of having reached a "technological frontier" that, given the existing state of knowledge, makes additional innovation very hard.[11] In that case, subsidies might only have a marginal positive effect since learning-by-doing, and the corresponding passage of time, might be necessary before the renewable technologies become truly competitive. Our study does not attempt to discriminate between these two hypotheses. Instead, we will study the optimal levels of innovation in renewable energy and the resulting length of the transition to a "green economy." We will also study how the length of this horizon is affected by imposing different tax/subsidy schemes. Before we introduce our model, we will discuss one alternative tool for measuring technological progress that we will use in our analysis later: the *learning (experience) curve.*

2.2 Learning Curves

An alternative way to measure technological progress involves the use of *learning curves.* These curves describe how marginal costs decline with cumulative production. Typically, this relationship is characterized empirically by a *"power law"* of the form

$$P_t = P_0 X^{-\alpha} \tag{1}$$

where P_0 is the initial price (*\$ cost of* first *MW of sales),* X is the cumulative production up to year t, and $2^{-\alpha}$ is the *progress ratio* (PR). For each doubling of the cumulative production (sales), the cost declines to $PR\%$ of its previous value. Taking logarithms on both sides results in a straight line if logarithmic axes are used; i.e., $\ln P_t = \ln P_0 - \alpha \ln X$.

[11] Popp (2002) notes that while energy prices did not peak until 1981, patenting activity in a variety of renewable energy sources peaked in the late 1970's. That patenting activity drops before prices might be an indication of diminishing returns to R&D.

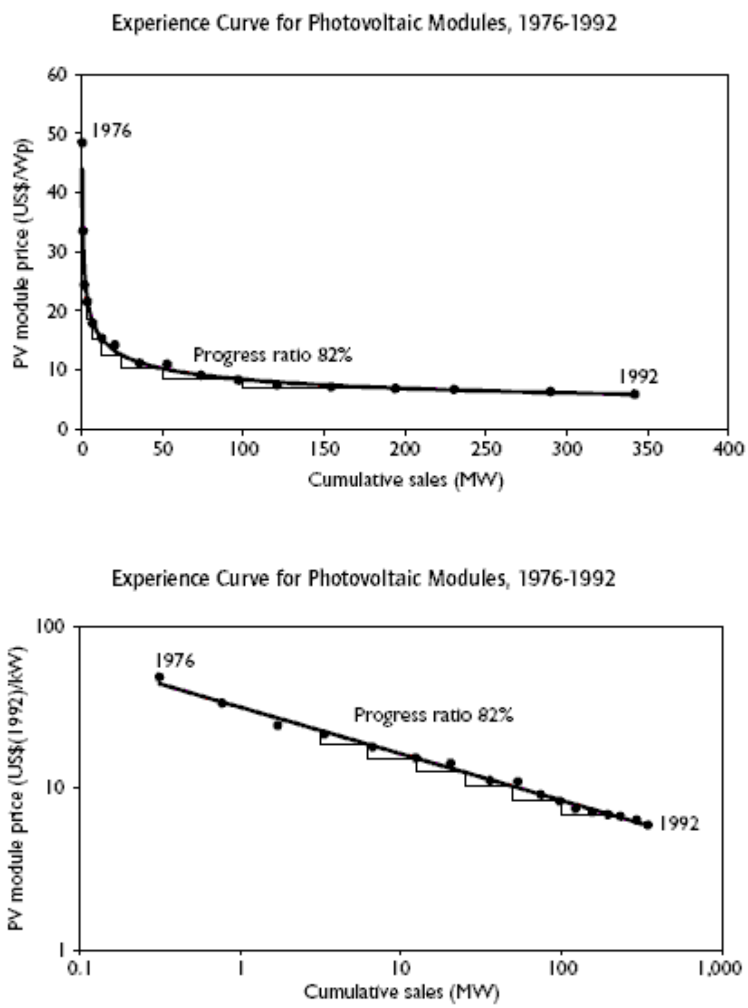

Figure 5: PV modules (International Energy Agency, 2000)

As an example, Figure 5 provides a learning curve for the price of photovoltaic modules between 1976 and 1992.

The apparent decline in costs might be due to several reasons, including process innovation, learning-by-doing, economies of scale, product innovation/redesign, input price declines, etc. Learning curves aggregate these factors. Such tools can also be used to guide policy. As of today, no renewable energy source is directly competitive with fossil fuel for widespread energy production. However, we would expect the costs associated with producing fossil fuels to increase over time as the most easily-mined resources are depleted. On the other hand, the costs of renewable energy should decline as a result of research investments and also as the volume of renewable energy increases. At some point in the future, therefore, parity will be reached. Proponents of government subsidies argue that, by subsidizing renewable energy research, or renewable energy use, we can hasten the decline in costs of renewable energy and, as a result, speed up the path towards parity. It is important to note, however, that such subsidies involve several direct and indirect costs.[12] Later in our analysis we will imbed a version of a learning curve into a general equilibrium macroeconomic model. This will allow us to study the effects of innovation on economic growth. The next section introduces the main ingredients of the model.

3 The Macro Model

3.1 Production Technology

We model economic activity in continuous time, indexed by t. The state variables, the controls, and the technology variables thus are functions of t. We will usually simplify the notation, however, by omitting time as an explicit argument.

There is a single consumption good in the economy. We assume that the per capita output of the good can be written as a linear function of a per capita stock of capital k:[13]

$$y = Ak \tag{2}$$

[12] When it comes to policy, it is worth mentioning that there is no reason to believe that subsidies to renewable energy use "bend down" experience curves. At best, they could accelerate progress along the curve. By contrast, direct R&D subsidies might reduce costs more directly. Nevertheless, even if such subsidies succeed in making new energy sources more competitive, they are not necessarily worthwhile. For example, we must also consider other costs associated with the switch, such as the need to replace existing capital tied to current fuel sources, the opportunity costs of subsidies, and the fact that learning-by-doing takes time, not just volume of production. We need a general equilibrium economy-wide model in order to quantify such opportunity costs and the effects of subsidies on other sectors, as well as the intertemporal benefits. The goal of this paper is to provide such a model.

[13] We assume that technological progress allows the "productive services" supplied by inputs to expand even if the physical inputs stop growing. In particular, we implicitly assume that labor input can be expanded through investment in human capital even if hours and number of employees remain fixed. Hence, the marginal product of capital does not decline as k accumulates.

We assume that capital depreciates at the rate δ, while investment in new capital is denoted by i:

$$\dot{k} = i - \delta k \tag{3}$$

Energy is also needed to produce output. At each moment in time, the ratio of energy to capital inputs is fixed. Denote the per capita energy derived from fossil fuel resources that is used to produce goods by $R \geq 0$. Per capita renewable energy supplied by the backstop technology $B \geq 0$ is a perfect substitute for the energy produced from fossil fuel burning. Thus, we assume that at each moment of time:

$$R + B = y \tag{4}$$

Letting c denote per capita consumption, we assume that the lifetime utility function is given by:

$$U = \max \int_0^\infty e^{-\beta\tau} \frac{c(\tau)^{1-\gamma}}{1-\gamma} \, d\tau \tag{5}$$

The term $e^{-\beta\tau}$ acts as a discount factor, capturing the fact that utility from future consumption is less valuable than today's consumption.

3.2 Fossil Fuel Supply

Let Q denote the (exogenous) population and labor supply and assume that it grows at the constant rate π. The total fossil fuel used will then be QR. Following Heal (1976) and Solow and Wan (1976), we assume that the most easily-mined, or the richest deposits or fields, tend to be exhausted first. The marginal resource costs of extraction then increase with the total quantity of resources mined to date, S, which is also the integral of QR:

$$\dot{S} = QR \tag{6}$$

Heal introduced the idea of an increasing marginal cost of extraction to show that the optimal price of an exhaustible resource begins above marginal cost, and falls toward it over time.[14]

We modify the resource depletion model to also allow for technical change in mining exploration. The marginal cost of extraction, $g(S, N)$, depends not only on S but also on the state of technical knowledge N. It is useful to define the energy supplies in efficiency units. Improvements in energy efficiency then also will lead to reduction in the per-unit cost $g(S, N)$ of supplying an additional unit of R. Investment in mining technology, or the efficiency with which fossil fuel is used to provide useful energy services, leads to an accumulation of knowledge:

$$\dot{N} = n \tag{7}$$

We then assume that $g(S, N)$ is given by the following function:

$$g(S, N) = \alpha_0 + \frac{\alpha_1}{\bar{S} - S - \alpha_2/(\alpha_3 + N)} = \alpha_0 + \frac{\alpha_1(\alpha_3 + N)}{(\bar{S} - S)(\alpha_3 + N) - \alpha_2} \tag{8}$$

illustrated in Figure 6. For a given state of technical knowledge N, the maximum fossil fuel resource that can be extracted is given by $\bar{S} - \alpha_2/(\alpha_3 + N)$. The terms $\alpha_0, \alpha_1, \alpha_2$ and α_3 in (8) are parameters.

The absolute maximum fossil fuel available is given by $\bar{S}$, and this is only available asymptotically as the stock of investment in new fossil fuel technology $N \to \infty$. Even then, to exploit all the technically available resources $\bar{S}$, would incur arbitrarily large costs.

For the later analysis, it also is useful to derive the partial derivatives of the fossil fuel cost function $g(S, N)$. The fist partial derivatives are given by

$$\frac{\partial g}{\partial S} = \frac{\alpha_1(\alpha_3 + N)^2}{[(\bar{S} - S)(\alpha_3 + N) - \alpha_2]^2} > 0 \tag{9}$$

and

$$\frac{\partial g}{\partial N} = -\frac{\alpha_1 \alpha_2}{[(\bar{S} - S)(\alpha_3 + N) - \alpha_2]^2} < 0 \tag{10}$$

[14] This claim is rigorously proved in Oren and Powell (1985).

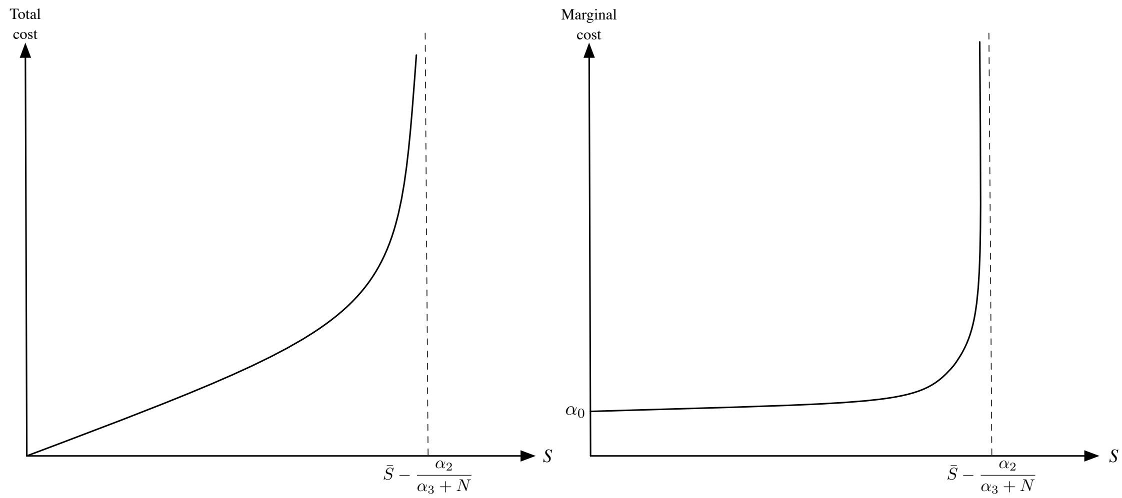

Figure 6: Cost of energy from fossil fuels

so that increases in S increase marginal cost, while improved technology reduces the costs of providing fossil fuel energy. The second order partial derivatives with respect to S and N are given by

$$\frac{\partial^2 g}{\partial S^2} = \frac{2\alpha_1(\alpha_3 + N)^3}{[(\bar{S} - S)(\alpha_3 + N) - \alpha_2]^3} > 0 \tag{11}$$

and

$$\frac{\partial^2 g}{\partial N^2} = \frac{2\alpha_1\alpha_2(\bar{S} - S)}{[(\bar{S} - S)(\alpha_3 + N) - \alpha_2]^3} > 0 \tag{12}$$

In particular, this function implies that cumulative exploitation S increases fossil fuel energy costs at an increasing rate, while investment in fossil fuel technology decreases costs at a decreasing rate. In fact, we can conclude from (10) that $\partial g/\partial N \to 0$ as $N \to \infty$. The latter fact should imply that eventually it becomes uneconomic to invest further in reducing the costs of fossil fuel energy. Thus, fossil fuel resources will likely be abandoned long before all known deposits are exhausted as rising costs make renewable energy technologies more attractive.

Finally, the cross second partial derivative will be given by

$$\frac{\partial^2 g}{\partial N \partial S} = -\frac{2\alpha_1\alpha_2(\alpha_3 + N)}{[(\bar{S} - S)(\alpha_3 + N) - \alpha_2]^3} < 0 \tag{13}$$

Hence, investment in fossil fuel technology delays the increase in costs of fossil fuel energy accompanying increased exploitation.

For energy to be productive on net, we need the value of output produced from energy input to exceed the costs of producing that energy input. In particular, if only fossil fuel is used to provide energy input, we must have $1 > g(S, N)$. The function (8) assumed above implies that exhaustion of fossil fuel resources must eventually increase costs $g(S, N)$ so that this constraint is violated.

3.3 Backstop Renewable Energy Technologies

Motivated by the analysis that uses learning curves, we assume that the marginal cost p (measured in terms of goods) of the energy services produced using the backstop technology declines as new knowledge is gained. Following the literature examining learning-by-doing, we assume that experience constructing capital using renewable energy input is the primary factor in lowering the amount of such capital required to harvest the energy needed to produce a given level of output. Even so, there is a limit, Γ_2, determined by physical constraints, below which p cannot fall. Explicitly, using H to denote the stock of knowledge about backstop energy production, and Γ_1 to denote the initial value of p (when $H = 0$), we assume:

$$p = \begin{cases} (\Gamma_1 + H)^{-\alpha} & \text{if } H \leq {\Gamma_2}^{-1/\alpha} - \Gamma_1, \\ \Gamma_2 & \text{otherwise} \end{cases} \tag{14}$$

for constant parameters Γ_1, Γ_2 and α. We assume that ${\Gamma_1}^{-\alpha} > g(0, 0)$, so that renewable energy is initially noncompetitive with fossil fuels.

We allow for technological progress to reduce the cost of renewable energy through a learning curve. In our formulation, some direct R&D expenditure j can accelerate the accumulation of knowledge about the renewable technology:[15]

$$\dot{H} = \begin{cases} B(1+\psi j) & \text{if } H \leq \Gamma_2^{-1/\alpha} - \Gamma_1, \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

In particular, once H reaches its upper limit, further investment in the technology would be worthless and we should have $j = 0$. The parameter ψ determines how investment in research enhances the accumulation of knowledge from experience.

As with fossil fuel, for the renewable backstop technology to be productive on net, we require $p < 1$. In effect, the renewable technology combines some output (effectively, capital) with an exogenous energy source (for example, sunlight, wind, waves or stored water) to produce an output that is more useful than the input.

3.4 The Optimization Problem

Goods are consumed, invested in k or H, or used for producing fossil fuel or backstop energy input. This leads to a resource constraint (in per capita terms):

$$c + i + j + n + g(S, N)R + pB = y \tag{16}$$

The objective function is maximized subject to the differential constraints (6), (7), (3) and (15) with initial conditions $S(0) = N(0) = 0$, $k(0) = k_0 > 0$ and $H(0) = 0$, the budget constraint (16), the definitions of output (2), energy input (4) and the evolution of the cost of the backstop energy supply (14). The control variables are c, i, j, R, n and B, while the state variables are k, H, S and N. Denote the corresponding co-state variables by q, η, σ and

[15] Klaassen et. al. (2005) studied the impact of public R&D and capacity expansion on cost reducing innovation for wind turbine farms in Denmark, Germany and the UK. They estimated a two-factor learning curve model that allowed for both learning-by-doing and direct R&D. They derive robust estimates suggesting that direct R&D is roughly twice as productive for reducing costs as is learning-by-doing. They interpret their results as enhancing the validity of the two-factor learning curve formulation. Kouvaritakis et al. (2000) used a two-factor learning specification that incorporates learning-by-doing effects as well as a relationship between technology performance and R&D expenditure.

ν. Let λ be the Lagrange multiplier on the budget constraint. We also need to allow for the possibility that either type of energy source is not used and investment in cost reduction for the energy technology is zero. To that end, let μ be the multiplier on the constraint $j \geq 0$, ω the multiplier on the constraint $n \geq 0$, ξ the multiplier on the constraint $R \geq 0$ and ζ the multiplier on the constraint $B \geq 0$. Finally, let χ be the multiplier on the constraint $H \leq {\Gamma_2}^{-1/\alpha} - \Gamma_1$ on the accumulation of knowledge about the renewable technology.

Define the current value Hamiltonian and thus Lagrangian by

$$\begin{aligned} \mathcal{H} = \frac{c^{1-\gamma}}{1-\gamma} + \lambda\left[Ak - c - i - j - n - g(S,N)R - (\Gamma_1 + H)^{-\alpha}B\right] + \epsilon(R + B - Ak) \\ + q(i - \delta k) + \eta B(1 + \psi j) + \sigma Q R + \nu n + \mu j + \omega n + \xi R + \zeta B + \chi[\Gamma_2^{-1/\alpha} - \Gamma_1 - H] \end{aligned} \tag{17}$$

The first order conditions for a maximum with respect to the control variables are:

$$\frac{\partial \mathcal{H}}{\partial c} = c^{-\gamma} - \lambda = 0 \tag{18}$$

$$\frac{\partial \mathcal{H}}{\partial i} = -\lambda + q = 0 \tag{19}$$

$$\frac{\partial \mathcal{H}}{\partial j} = -\lambda + \eta\psi B + \mu = 0; \mu j = 0, \mu \geq 0, j \geq 0 \tag{20}$$

$$\frac{\partial \mathcal{H}}{\partial n} = -\lambda + \nu + \omega = 0, \omega n = 0, \omega \geq 0, n \geq 0 \tag{21}$$

$$\frac{\partial \mathcal{H}}{\partial R} = -\lambda g(S,N) + \epsilon + \sigma Q + \xi = 0, \xi R = 0, \xi \geq 0, R \geq 0 \tag{22}$$

$$\frac{\partial \mathcal{H}}{\partial B} = -\lambda(\Gamma_1 + H)^{-\alpha} + \epsilon + \eta(1 + \psi j) + \zeta = 0, \zeta B = 0, \zeta \geq 0, B \geq 0 \tag{23}$$

The differential equations for the co-state variables are:

$$\dot{q} = \beta q - \frac{\partial \mathcal{H}}{\partial k} = (\beta + \delta)q - \lambda A + \epsilon A \tag{24}$$

$$\dot{\eta} = \beta\eta - \frac{\partial \mathcal{H}}{\partial H} = \beta\eta - \lambda\alpha(\Gamma_1 + H)^{-\alpha-1}B + \chi;$$
$$\chi[(\Gamma_2^{-1/\alpha} - \Gamma_1 - H] = 0, \chi \geq 0, H \leq \Gamma_2^{-1/\alpha} - \Gamma_1 \tag{25}$$

$$\dot{\sigma} = \beta\sigma - \frac{\partial \mathcal{H}}{\partial S} = \beta\sigma + \lambda\frac{\partial g}{\partial S}R \tag{26}$$

$$\dot{\nu} = \beta\nu - \frac{\partial \mathcal{H}}{\partial N} = \beta\nu + \lambda\frac{\partial g}{\partial N}R \tag{27}$$

We also recover the budget constraint (16) and the differential equations for the state variables, (3), (15), (6) and (7).

3.5 The Long Run Endogenous Growth Economy

Since the costs of using fossil fuel must rise as resources are depleted, ultimately energy is supplied using only the backstop renewable technology. In the very long run, the cost of the renewable energy source will be constant at $p = \Gamma_2$ and the stock of knowledge about renewable energy production H is no longer relevant. In this regime, the model becomes a simple endogenous growth model with investment only in physical capital. We retain the first order conditions (18), (19) and (23), the first co-state equation (24), the budget constraint (16) and the differential equation (3) for the only remaining state variable k. However, (23) changes to simply $\epsilon = \lambda\Gamma_2$. From (19) we will obtain $q = \lambda$ and hence $\dot{q} = \dot{\lambda}$, and the co-state equation (24) becomes

$$\dot{\lambda} = [\beta + \delta - (1 - \Gamma_2)A]\,\lambda \equiv \bar{A}\lambda \tag{28}$$

where $\bar{A}$ is a constant. If we are to have perpetual growth, we must have $c \to \infty$ as $t \to \infty$, which from (18) will require $\lambda \to 0$ and hence $\bar{A} < 0$, that is[16]

$$\Gamma_2 < 1 - \frac{\beta + \delta}{A} \tag{29}$$

[16] Note that (29) will require $A > (\beta+\delta)/(1-\bar{p}) > \beta+\delta$, which is the usual condition for perpetual growth in a simple linear growth model.

Condition (29) has an intuitive interpretation. With $B = y$ and $p = \Gamma_2$, $A(1 - \Gamma_2)$ equals output per unit of capital *net* of the costs of supplying the backstop energy input. To obtain perpetual growth, this must exceed the cost of holding capital measured by the sum of the depreciation rate (the explicit cost) and the time discount rate (the implicit opportunity cost). Hereafter, we assume (29) to be valid. The solution to (28) can be written

$$\lambda = \bar{K}e^{\bar{A}t} \tag{30}$$

for some constant $\bar{K}$ yet to be determined. Thus, in this final regime, the budget constraint, the first order condition (18) for c and (30) imply

$$\dot{k} = (\beta - \bar{A})k - \bar{K}^{-1/\gamma}e^{-\bar{A}t/\gamma} \tag{31}$$

The integrating factor for the differential equation (31) is $e^{(\bar{A}-\beta)t}$, so the solution can be written

$$k = C_0 e^{(\beta-\bar{A})t} + \frac{\gamma\bar{K}^{-1/\gamma}e^{-\bar{A}t/\gamma}}{\beta\gamma - \bar{A}(\gamma - 1)} \tag{32}$$

for another constant C_0. However, the transversality condition at infinity requires

$$\lim_{t\to\infty} e^{-\beta t}\lambda k = C_0 + \lim_{t\to\infty} \frac{\gamma\bar{K}^{-1/\gamma}e^{(-\bar{A}/\gamma+\bar{A}-\beta)t}}{\beta\gamma - \bar{A}(\gamma - 1)} = 0 \tag{33}$$

Equation (33) in turn requires

$$C_0 = 0 \text{ and } \bar{A}(\gamma - 1) < \beta\gamma \tag{34}$$

Note that since $\bar{A} < 0$ the inequality in (34) will be satisfied if $\gamma > 1$, while if $0 < \gamma < 1$, it will require

$$\Gamma_2 > 1 - \frac{\beta/(1-\gamma) + \delta}{A} \tag{35}$$

Thus, for $\gamma < 1$, the validity of (29) and (35) together require

$$1 - \frac{\beta + \delta}{A} > \Gamma_2 > 1 - \frac{\beta/(1-\gamma) + \delta}{A} \tag{36}$$

In summary, we conclude that the value of k in the final endogenous growth economy will be given by

$$k = \frac{\gamma \bar{K}^{-1/\gamma} e^{-\bar{A}t/\gamma}}{\beta\gamma - \bar{A}(\gamma - 1)} \tag{37}$$

with λ given by (30) and $\bar{K}$ is a constant yet to be determined.

For periods prior to the terminal endogenous growth regime just analyzed, note first that we cannot have $j > 0$ and $B = 0$. This follows from (20), since if $B = 0$, $\mu = \lambda > 0$ which implies $j = 0$. For empirically relevant parameter values, however, we can have a short interval of time where $B > 0$ and $j = 0$. Since $B > 0$ in this regime, learning by doing implies that the cost of renewable energy will decline.

Since the energy services of fossil fuels and the backstop renewable technology are perfect substitutes, the renewable technology will not be competitive with fossil fuels until the shadow price of energy in the fossil fuel regime equals the shadow price in the renewable backstop regime. When only fossil fuel is used, we assume that the productivity of investing in fossil fuel technology is high enough to sustain investments right up until the time the economy transitions to renewable energy. Although investments moderate the increase in fossil fuel costs, eventually depletion ensures that the shadow price of energy derived from fossil fuels rises to equal the initially higher cost of energy from renewable sources. At that point, the economy switches to use only renewable energy and all investment in, and use of, fossil fuel technologies ceases. We therefore conclude that the economy will pass through the regimes illustrated in the time line in Figure 7.

3.6 The Initial Fossil Fuel Economy

It is useful to consider next the regime where $R > 0$. Then (22) implies $\xi = 0$ and the shadow price of energy will be

$$\epsilon = \lambda g(S, N) - \sigma Q \tag{38}$$

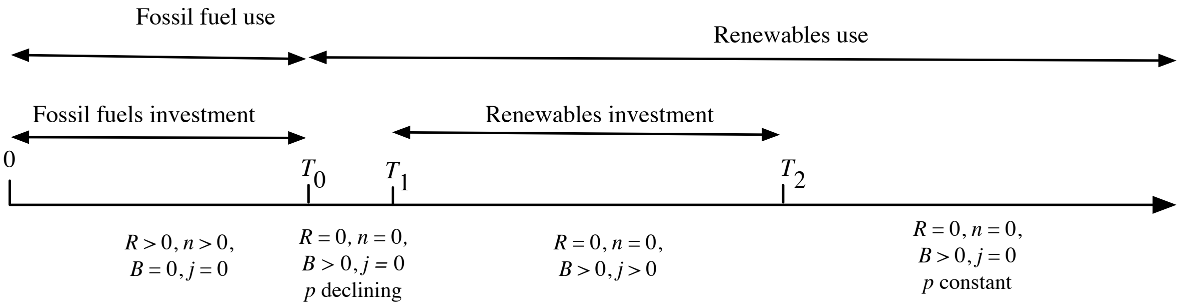

Figure 7: Regimes of energy use and investment

Since an increase in S raises the costs of fossil fuel, the co-state variable σ will be negative[17] while fossil fuels are used as an energy source. It then follows from (38) that the shadow price of energy ϵ is unambiguously positive.

We also assume parameter values are chosen so that investment in fossil fuel technology is productive, that is, $n > 0$. Then (21) implies $\omega = 0$ and hence $\nu = \lambda$. But then $\dot{\nu} = \dot{\lambda}$ and (27) implies

$$\dot{\lambda} = \beta\lambda + \lambda\frac{\partial g}{\partial N}R \tag{39}$$

If we also have $i > 0$, (19) will imply $\lambda = q$ and from (24) and (38), we will also have $\dot{\lambda} = (\beta + \delta + g(S,N)A - A)\lambda - \sigma QA$. Using (39) we then conclude

$$\left[\delta + g(S,N)A - \frac{\partial g}{\partial N}R - A\right]\lambda = \sigma QA \tag{40}$$

Note that since $\sigma < 0$ and $\lambda = c^{-\gamma} > 0$, a necessary condition for (40) to hold is that

$$\delta + g(S,N)A - \frac{\partial g}{\partial N}R < A \tag{41}$$

Since we have assumed, however, that $g(S,N)$ eventually increases above 1 as S grows, and $\partial g/\partial N < 0$, constraint (41) must eventually be violated and the economy will not use fossil fuels forever.

[17] Recall that if we use V to denote the maximized value of the objective subject to the constraints, the co-state variable σ will equal the partial derivative of V with respect to the corresponding state variable, S.

Substituting $R = Ak$ into (40), we obtain an equation relating N and k. When there is active investment in two types of capital (here k and N), the investment has to maintain a relationship between the two stocks. Differentiating the resulting expression with respect to time, substituting for $\dot{N}, \dot{\lambda}/\lambda = \dot{\nu}/\nu, \dot{S}, \dot{\sigma}$ and $\dot{Q} = \pi Q$ (since the exogenous growth rate of Q is π), and using (40), we obtain a condition relating the two types of investments (i and n) in the initial fossil fuel economy:

$$\lambda \left[\frac{\partial g}{\partial N}(n + \delta k + \frac{\sigma Q A k}{\lambda} - i) - \frac{\partial^2 g}{\partial S \partial N} Q A k^2 - \frac{\partial^2 g}{\partial N^2} n k \right] = \sigma \pi Q \tag{42}$$

We obtain a second relationship from the budget constraint. Specifically, using the result that $j = 0$ if $B = 0$, the first order condition (18) for c, the production function (2), the energy input demand requirement (4) the budget constraint (16) implies:

$$i = Ak[1 - g(S, N)] - \lambda^{-1/\gamma} - n \tag{43}$$

Substituting (43) into (42), we then obtain an equation to be solved for energy technology investment n in the fossil fuel regime:

$$\begin{aligned} &n\lambda \left(\frac{\partial^2 g}{\partial N^2} k - 2 \frac{\partial g}{\partial N} \right) = \\ &\lambda \left[\frac{\partial g}{\partial N} [k(\delta + g(S, N)A - A + \frac{\sigma Q A}{\lambda}) + \lambda^{-1/\gamma}] - \frac{\partial^2 g}{\partial S \partial N} Q A k^2 \right] - \sigma \pi Q \end{aligned} \tag{44}$$

Since $\partial g/\partial N < 0$ and $\partial^2 g/\partial N^2 > 0$, the coefficient of n on the left hand side of (76) is positive. From the budget constraint (43), $\delta k + Ak(g - 1) + \lambda^{-1/\gamma} = \delta k - i - n \leq \delta k - n$. Then if

$$-\frac{\partial^2 g}{\partial S \partial N} Q A k^2 + \frac{\partial g}{\partial N}(\delta + \frac{\sigma Q A}{\lambda})k - \sigma \pi Q > 0 \tag{45}$$

we can conclude that $n > 0$ as hypothesized.[18] Using the solution for n and the current

[18] Since $\partial^2 g/\partial S \partial N < 0$ and $\sigma < 0$, the quadratic in k in (45) has a positive second derivative and positive intercept, so even if $\delta + \sigma Q A/\lambda > 0$, so the roots are both positive, we conclude that (45) must hold for large k. For small values of k, we are likely to have $\dot{k} = i - \delta k > 0$, in which case the right hand side of (76) is guaranteed to be positive.

values of the state and co-state variables, (43) can be solved for i.

In summary, we conclude that the initial period of fossil fuel use with both $i > 0$ and $n > 0$ produces five differential equations for k, S, N, σ, and λ:

$$\dot{k} = i - \delta k \tag{46}$$

$$\dot{S} = QAk \tag{47}$$

$$\dot{N} = n \tag{48}$$

$$\dot{\sigma} = \beta\sigma + \lambda\frac{\partial g}{\partial S}Ak \tag{49}$$

$$\dot{\lambda} = \lambda(\beta + \delta + (g(S, N) - 1)A) - \sigma QA \tag{50}$$

together with the exogenous population growth $Q = Q_0 e^{\pi t}$.

3.7 The Intermediate Economy with Renewables and Technological Progress

We next consider the regimes where $B = Ak > 0, j \geq 0$ and $H < \Gamma_2^{-1/\alpha} - \Gamma_1$. For $B > 0$, (23) implies $\zeta = 0$, while $H < \Gamma_2^{-1/\alpha} - \Gamma_1$ and (25) imply $\chi = 0$. Considering first the majority of this regime where $j > 0$, (20) implies $\mu = 0$, and from (19) and (20), $q = \lambda = \eta\psi Ak$. Thus, when $j > 0$ the shadow price of energy becomes

$$\epsilon = \lambda(\Gamma_1 + H)^{-\alpha} - \frac{\lambda(1 + \psi j)}{\psi Ak} \tag{51}$$

Substituting (51) into (24) and noting that $q = \lambda$ implies $\dot{q} = \dot{\lambda}$, we obtain

$$\frac{\dot{\lambda}}{\lambda} = \beta + \delta - A(1 - (\Gamma_1 + H)^{-\alpha}) - \frac{1}{\psi k} - \frac{j}{k} \tag{52}$$

From (25) with $\lambda = \eta\psi Ak$ and $B = Ak$, and using $\dot{k} = i - \delta k$, we obtain

$$\frac{\dot{\lambda}}{\lambda} = \beta - \delta - \alpha(\Gamma_1 + H)^{-\alpha-1}\psi(Ak)^2 + \frac{i}{k} \tag{53}$$

Equating (52) and (53), we obtain an expression for total investment, $i + j$, as a function of k and H

$$i + j = 2\delta k - \frac{1}{\psi} - Ak(1 - (\Gamma_1 + H)^{-\alpha}) + \alpha\psi A^2k^3(\Gamma_1 + H)^{-\alpha-1} \tag{54}$$

The budget constraint and the first order condition (18) for c then provide a second equation for $i + j$:

$$i + j = Ak(1 - (\Gamma_1 + H)^{-\alpha}) - \lambda^{-1/\gamma} \tag{55}$$

Substituting (55) into (54), we obtain an equation relating H and k:

$$\alpha\psi A^2k^3(\Gamma_1 + H)^{-\alpha-1} + 2k[\delta - A(1 - (\Gamma_1 + H)^{-\alpha})] + \lambda^{-1/\gamma} - \frac{1}{\psi} = 0 \tag{56}$$

Once again, when there is active investment in two types of capital (here k and H), the investment has to maintain a relationship between the two stocks.[19]

Differentiating (56) with respect to t, and substituting $\dot{k} = i - \delta k$, $\dot{H} = Ak(1 + \psi j)$ and for $\dot{\lambda}/\lambda$ using (52) we obtain a second relationship between i and j and the current values of k, H and λ:

$$\begin{aligned}
&\left[2[\delta - A(1 - (\Gamma_1 + H)^{-\alpha})] + 3\alpha\psi(Ak)^2(\Gamma_1 + H)^{-\alpha-1}\right] i + \\
&\left[\frac{\lambda^{-1/\gamma}}{\gamma k} - \alpha\psi(Ak)^2(\Gamma_1 + H)^{-\alpha-1}[2 + (1+\alpha)\psi Ak^2(\Gamma_1 + H)^{-1}]\right] j \\
&= \left[2[\delta - A(1 - (\Gamma_1 + H)^{-\alpha})] + 3\alpha\psi(Ak)^2(\Gamma_1 + H)^{-\alpha-1}\right] \delta k \\
&+ \alpha(Ak)^2(\Gamma_1 + H)^{-\alpha-1}[2 + (1+\alpha)\psi Ak^2(\Gamma_1 + H)^{-1}] \\
&+ \frac{\lambda^{-1/\gamma}}{\gamma}[\beta + \delta - A(1 - (\Gamma_1 + H)^{-\alpha}) - \frac{1}{\psi k}]
\end{aligned} \tag{57}$$

[19]It can be shown that (56) has a unique real solution for k in terms of H and the parameters.

The two equations (55) and (57) can then be solved for i and j given current values for k, H and λ. Using the solutions for the investment levels, we can then obtain the differential equations governing the evolution of k, H and λ in region 2, which, for convenience are summarized below:

$$\dot{k} = i - \delta k \tag{58}$$

$$\dot{H} = Ak(1 + \psi j) \tag{59}$$

$$\dot{\lambda} = \lambda \left[\beta + \delta - A(1 - (\Gamma_1 + H)^{-\alpha}) - \frac{1 + \psi j}{\psi k} \right] \tag{60}$$

Now consider the beginning of the renewable energy regime where $j = 0$. Here we will have from (20) that $\mu = \lambda - \eta\psi B \geq 0$ with $\lambda = \eta\psi B$ at the upper boundary where the constraint on j is just binding. In the interior of this region where $n = j = 0 = R$, the budget constraint (16) will imply $i = Ak(1 - p) - c$ with $p = (\Gamma_1 + H)^{-\alpha}$ and $c = \lambda^{-1/\gamma}$. Also, the shadow price of energy obtained from (23) will now be given by $\epsilon = \lambda p - \eta$ and we retain $q = \lambda$, but we will no longer have $\lambda = \eta\psi Ak$. The differential equations governing the evolution of k, H, λ and η now become:

$$\dot{k} = Ak[1 - (\Gamma_1 + H)^{-\alpha}] - \lambda^{-1/\gamma} - \delta k \tag{61}$$

$$\dot{H} = Ak \tag{62}$$

$$\dot{\lambda} = \lambda \left[\beta + \delta - A(1 - (\Gamma_1 + H)^{-\alpha}) \right] - \eta A \tag{63}$$

$$\dot{\eta} = \beta\eta - \lambda\alpha(\Gamma_1 + H)^{-\alpha-1} Ak \tag{64}$$

3.8 Boundary conditions

In the numerical analysis, the economy begins with known values of the state variables $k(0), S(0)$ and $N(0)$ at $t = 0$. However, the initial values of the co-state variables $\lambda(0)$ and $\sigma(0)$ are unknown. Similarly, the initial value of the co-state variable $\eta(T_0)$ at T_0 is unknown. These all have to be guessed and the model solved forward. The values of the co-state variables at the transition times are then compared with their target values and the guesses are modified until all the targets are attained to the desired numerical accuracy. In this section, we discuss what the target values ought to be.

First, note that at T_0, $H = j = 0 = \sigma$. Using (51) and (38) and the requirement that the shadow price of energy has to be continuous across the region boundaries then implies

$$\Gamma_1^{-\alpha} - \frac{\eta}{\lambda} = \frac{\epsilon}{\lambda} = g(S, N) \tag{65}$$

For a given value of $\eta(T_0)$, (65) would then determine a value of T_0 and corresponding values of $k(T_0), S(T_0), N(T_0), \sigma(T_0)$ and $\lambda(T_0)$ using the differential equations (46)–(50). The calculated value of $\sigma(T_0)$ would then need to be compared to its target value of 0.

The calculated values for $k(T_0)$ and $\lambda(T_0)$ together with $H = 0$ and the guessed value of $\eta(T_0)$ will then provide starting values for the differential equations (61)–(64) in the next regime.[20] As already noted above, the upper boundary T_1 of this region will occur where $\lambda = \eta\psi Ak$.

Once T_1 has been reached, the differential equations change to (58)–(60). Again, the values of k, H, and λ will be continuous across the T_1 boundary. We also require that the initial calculated value for j in the third regime, using (55) and (57), equal its target value of 0. The upper boundary of this third region, T_2, will occur where $p = (\Gamma_1 + H)^{-\alpha} = \Gamma_2$, which will determine the value of H at T_2, namely $H = \Gamma_2^{-1/\alpha} - \Gamma_1$. We will also know the values of k and λ at T_2 (up to the unknown constant $\bar{K}$) since they must be continuous across the boundary and therefore must equal (37) and (30) respectively. One of these equations, say (30), can be used to solve for $\bar{K}$ and then (37) will provide a third target value.

Note that in total we have three targets –$\sigma(T_0) = 0, j(T_1) = 0$ and $k(T_2)$,which equals the corresponding calculated value implied by $\lambda(T_2)$– that can be used to determine appropriate

[20] It may also be worth noting that a number of control variables will not be continuous across the $t = T_0$ boundary. To begin with, R will jump from equalling $Ak > 0$ right up until T_0 to a value of zero at T_0 and beyond. Correspondingly, B will jump from zero before T_0 to $Ak > 0$ from T_0 on. In addition, n will jump from being strictly positive as $t \to T_0$ to being zero at T_0. Conversely, j will jump from zero for $t < T_0$ to being positive at T_0.

initial values for the three variables $\lambda(0), \sigma(0)$ and $\eta(T_0)$. In practice, we guess values for the latter and iterate until the targets are attained.

3.9 Calibration

In order to quantitatively evaluate different policy scenarios, we first need to calibrate the theoretical model. This involves assigning numerical values to certain parameters in a way that make the model consistent with observations from the actual world economy. By definition, we start the economy with $S = N = H = 0$ and with $Q = Q_0$. For convenience, we take the current population $Q_0 = 1$ and effectively measure future population as multiples of the current level. We will assume that the population growth rate is 1 percent.[21]

In line with standard assumptions made to calibrate growth models, we assume a time discount factor $\beta = 0.05$. From previous analyses, we would expect the coefficient of relative risk aversion γ to lie between 1 and 10, but there is no strong consensus on what the value should be. As we explain in more detail below, we will allow γ to adjust to ensure we match the initial share of consumption in GDP.

To calibrate values for the initial production, capital and energy quantities we used data from the EIA,[22] the *Survey of Energy Resources 2007* produced by the *World Energy Council*,[23] and *the GTAP 7 Data Base* produced by the *Center for Global Trade Analysis* at Purdue university's Department of Agricultural Economics.[24] The last mentioned data source is useful for our purposes because it provides a consistent set of international accounts that also takes account of energy flows.

One of the first issues we need to address is that national accounts include government spending in GDP, which does not appear in the model.[25] We therefore subtracted government

[21]This is consistent with a simple extrapolation of recent world growth rates reported by the Food And Agriculture Organization of the United Nations, http://faostat.fao.org/site/550/default.aspx

[22]International data is available at http://www.eia.doe.gov/emeu/international/contents.html

[23]This is available at http://www.worldenergy.org/publications/survey_of_energy_resources_2007/default.asp The data are estimates as of the end of 2005.

[24]Information on this can be found at https://www.gtap.agecon.purdue.edu/databases/v7/default.asp The GTAP 7 data base pertains to data for 2004.

[25]Note that in the GTAP data base, aggregate world exports equal aggregate world imports so world GDP

spending from the GDP measures before calibrating the remaining variables. Conceptually, this would be correct if the utility obtained from government spending were additively separable from the utility obtained from private consumption and government spending was financed by lump sum taxes. In practice, neither of these assumptions is valid and government activity (apart from energy taxes or subsidies, which will be considered explicitly later) would affect the equilibrium of the model.

After excluding government, the investment share of private sector expenditure is 0.2575. Effectively defining units so that aggregate output is 1, we therefore identify 0.2575 as the sum $i+n$ at $t=0$. We would expect most of this to be investment in capital used to produce output rather than fossil fuel exploration and development.

Converting the GTAP data base estimates of the total capital stock to units of GDP, we obtain the initial condition $k(0) = 3.2759$. We also use the GTAP depreciation rate on capital of 4 percent. Also, if we choose units so that output equals 1, the parameter A would equal the ratio of output to capital, that is, $A \approx 0.3053$.

From the budget constraint, the difference between total output and the sum of the investments, namely 0.7425 would equal consumption plus the current costs gR of supplying fossil fuels. We separated these two components using sectoral data from the GTAP data base. Specifically, we classified "energy expenditure" as combined spending on the primary fuels coal, oil and natural gas and the energy commodity transformation sectors of refining, chemicals, electricity generation and natural gas distribution. The current cost of fossil energy was then set equal to the expenditure on these sectors that was classified as consumption rather than investment. This produced a value for $gR = 0.0558$.

Subtracting the initial value for gR from 0.7425 we obtain the initial value of $c(0) = 0.6867$. As noted above, the normal method of solving the optimal control problem would involve specifying values for the parameters and the state variables and then solving for values of the co-state variables that allow us to hit required terminal values. The value for $c(0)$ would then follow from the first order condition $\lambda(0) = c(0)^{-\gamma}$. To obtain a particular

equals consumption plus investment plus government expenditure.

value for $c(0)$ we then need to free up an additional parameter. As already noted above, we will introduce $c(0)$ as a new target and adjust the value of γ as $\lambda(0)$ changes to ensure that $\lambda(0) = c(0)^{-\gamma}$ always remains valid.

After we set the initial values of S and N to zero, the initial value for gR also would imply

$$\frac{0.0558}{R} = \alpha_0 + \frac{\alpha_1}{\bar{S} - \alpha_2/\alpha_3} \tag{66}$$

We can obtain a value for total fossil fuel production, R, from the EIA web site. It gives world wide production of oil in 2004 of 175.948 quads (where one quad equals 10^{15} BTU), of natural gas 100.141 quads and of coal 116.6 quads. Summing these gives a total of 392.689 quads. We then choose energy units so that the initial value of $R = 1$.

To obtain an estimate of total fossil fuel resources $\bar{S}$ in the same units, we begin with the proved and estimated additional resources in place from the World Energy Council. The millions of tons of coal, millions of barrels of oil, extra heavy oil, natural bitumen and oil shale and trillions of cubic feet of natural gas given in that publication were converted to quads using conversion factors available at the EIA. The result is 115.2 quintillion BTU, or almost 300 times the annual worldwide production of fossil fuels in 2004. These resources are nevertheless relatively small compared to estimates of the volume of methane hydrates that may be available. Although experiments have been conducted to test methods of exploiting methane hydrates, a commercially viable process is yet to be demonstrated. Partly as a result, resource estimates vary widely. According to the National Energy Technology Laboratory (NETL),[26] the United States Geological Survey (USGS) has estimated potential resources of about 200,000 trillion cubic feet in the United States alone. According to Timothy Collett of the USGS,[27] current estimates of the worldwide resource in place are about 700,000 trillion cubic feet of methane. Using the latter figure, this would be equivalent to 719.6 quintillion BTU. Adding this to the previous total of oil, natural gas and coal resources yields a value for $\bar{S} = 834.8$ quintillion BTU or around 2125.8986 in terms of the

[26] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/about-hydrates/estimates.htm

[27] http://www.netl.doe.gov/kmd/cds/disk10/collett.pdf

energy units defined so that $R = 1$.

We still need to specify values for the α_i parameters in the g function. Equation (66) with $R \equiv 1$ will give us one equation in four unknowns. Noting that we can interpret $\bar{S} - \alpha_2/\alpha_3$ as the initial level of fossil fuel extraction S at which marginal costs of extraction $g(S, 0)$ would become unbounded, we associate $\bar{S} - \alpha_2/\alpha_3$ with current proved and connected reserves of fossil fuel.[28] A recent report from Cambridge Energy Research Associates (CERA, 2009),[29] for example, gives weighted average decline rates for oil production from existing fields of around 4.5 percent per year. They also note that this figure is dominated by a small number of "giant" fields and that, "the average decline rate for fields that were actually in the decline phase was 7.5 percent, but this number falls to 6.1 percent when the numbers are production weighted." Hence, we shall use 6 percent as a decline rate for oil fields. If we use United States production and reserve figures as a guide, we find that natural gas decline rates are closer to 8 percent per year but coal mine decline rates are closer to 6 percent per year. In accordance with these figures, we assume the ratio of fossil fuel production to proved and connected reserves equals the share weighted average of these figures, namely $(175.948 * 0.06 + 100.141 * 0.08 + 116.6 * 0.06)/392.689 = 0.0651$. Thus, in terms of the energy units defined so that $R = 1$, the initial target value of $\bar{S} - \alpha_2/\alpha_3$ would equal $1/0.0651 = 15.361$. Using the previously calculated value for $\bar{S}$, this leads to $\alpha_2/\alpha_3 = 2110.538$.

We can obtain two more equations by specifying the partial derivatives of g at $t = 0$. Using GTAP data on capital shares by sector, we estimate that around 6.5 percent of annual investment occurs in the oil, natural gas, coal, electricity, and gas distribution sectors.[30] We noted above that in the GTAP data, total investment $i + n = 0.2575$, implying that $n \approx 0.0167$ in private sector output units. We assume that this level of investment at

[28] Note that current official reserves are not the relevant measure since many of these are not connected and thus are unavailable for production without further investment, denoted n in the model.

[29] "The Future of Global Oil Supply: Understanding the Building Blocks," Special Report by Peter Jackson, Senior Director, IHS Cambridge Energy Research Associates, Cambridge, MA.

[30] Since we have defined R to be energy services input, investments in energy efficiency in addition to mining increase the effective supply of fossil fuels. Hence, we include investments in the energy transformation sectors. While some of these would not increase energy efficiency, some investments in the transportation and manufacturing sectors that have not been included would be aimed at raising energy efficiency.

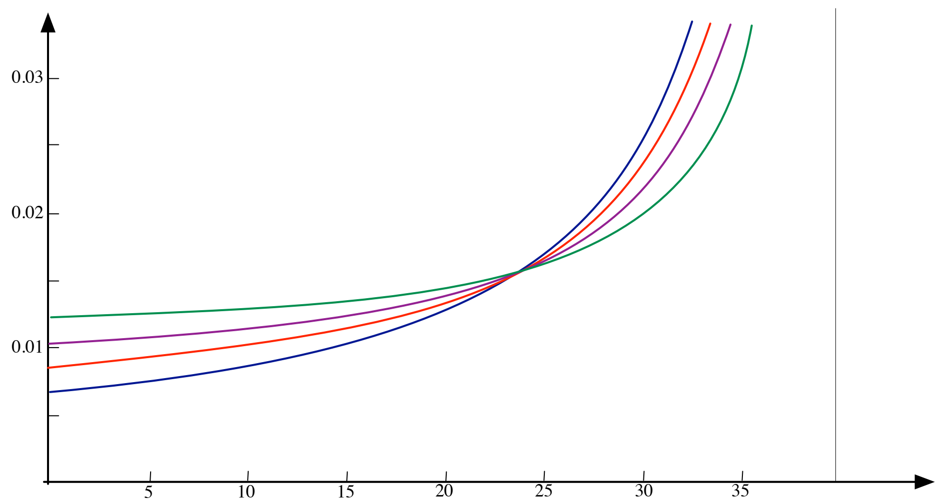

Figure 8: $g(S, N)$ for $N = 0.3$ and different values of g_S and g_N

$t = 0$ is sufficient to replace mined resources and allow for growth in total annual fossil fuel production equivalent to the average annual growth over 2004-08 of around 2.36%.[31] Specifically, with $\alpha_2/\alpha_3 = 2110.538$, we assume that $\alpha_2/(\alpha_3 + 0.0167) = 2109.195$, which implies $\alpha_3 \approx 25.852$. The previously calculated value for α_2/α_3 then implies $\alpha_2 \approx 54561.15$. Given values for α_2 and α_3, the ratio g_N/g_S then also is determined, but the individual values of g_S and g_N can still vary. As they do, α_0 and α_1 also will vary. Figure 8 illustrates the curves at $t = 0$ for values of g_S ranging from 0.0004 (the closest to a right angled shape) to 0.001 (the furthest from a right angled shape). We assumed $g_S = 0.001$ for the following calculations.

Turning next to the learning curve (14), the literature provides a range of estimates for α. An online calculator provided by NASA[32] gives a range of learning percentages between 5 and 20% depending on the industry. A learning percentage of x, which corresponds to a value of $\alpha = -ln(1 - x)/ln(2)$, has the interpretation that a doubling of the experience measure will lead to a cost reduction of x percent. Thus, $x = 0.2$ is equivalent to $\alpha = 0.322$ while $x = .05$ corresponds to $\alpha = 0.074$. In a study of wind turbines, Coulomb and Neuhoff

[31]These calculations are again based on data from the EIA.
[32]Available at http://cost.jsc.nasa.gov/learn.html

(2006)[33] found values of α of 0.158 and 0.197. In a 1998 paper, Grübler and Messner[34] found a value for $\alpha = .36$ using data on solar panels. In a 2008 paper in *The Energy Journal*, van Bentham et. al.[35] report several studies finding a learning percentage of around 20% ($\alpha = 0.322$) for solar panels. For our base case, we will take $\alpha = 0.37$.

The other parameter affecting the incentive to invest in renewable energy sources is the initial value $\Gamma_1^{-\alpha}$ of the cost of using renewable energy as the primary energy source. Using a document available from the Energy Information Administration (EIA)[36] the cost of new onshore wind capacity is about double the cost of combined cycle gas turbines (CCGT), while offshore wind is around four times as expensive, solar thermal more than five times as expensive and solar photovoltaic more than six times as expensive. However, these costs do not take account of the lower average capacity factor of intermittent sources such as wind or solar. The same document gives a fixed O&M cost of onshore wind that is around two and a half times the corresponding fixed O&M for CCGT, although the latter also has fuel costs. The corresponding ratio is around 7 for offshore wind, while fixed O&M for solar photovoltaic are similar to the fixed O&M for CCGT. As a rough approximation, we will assume $\Gamma_1^{-\alpha}$ is around 4 times the initial value of g. In accordance with the EIA assumptions, we also assume that, in the long run, the renewable technologies can experience a five-fold reduction in costs, so $\Gamma_2 = \Gamma_1^{-\alpha}/5$. This would result in an energy cost that is below the current cost of fossil fuel technologies.

Finally, we need to specify a value for ψ, the relative effectiveness of direct investment in research versus learning by doing in accumulating knowledge about new energy technologies. Klaassen et. al. (2005)[37] estimated a model that allowed for both learning-by-doing and

[33] Louis Coulomb and Karsten Neuhoff, "Learning Curves and Changing Product Attributes: the Case of Wind Turbines", University of Cambridge: Electricity Policy Research Group, Working Paper EPRG0601.

[34] Arnulf Grübler and Sabine Messner, "Technological change and the timing of mitigation measures", *Energy Economics* 20, 1998, 495–512

[35] "Learning-by-doing and the optimal solar policy in California," Arthur van Benthem, Kenneth Gillingham and James Sweeney, 29(3) 2008, 131-152

[36] *Assumptions to the Annual Energy Outlook, 2009*, "Electricity Market Module," Table 8.2, available at http://www.eia.doe.gov/oiaf/aeo/assumption/pdf/electricity.pdf#page=3

[37] Klaassen, Ger, Asami Miketa, Katarina Larsen and Thomas Sundqvist, "The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom," *Ecological Economics*, 54 (2005) 227–240

direct R&D. Although they assume the capital cost is multiplicative in total R&D and cumulative capacity, while we assume the *change* in knowledge is multiplicative in new R&D and cumulative capacity, we can take their parameter estimates as a guide. They find direct R&D is roughly twice as productive for reducing costs as is learning-by-doing.[38] Consequently, we assume that $\psi = 2$.

The results from the calibrated version of our model economy are summarized below. Absent any government intervention in the economy, the transition to a renewable energy regime occurs after $T_0 = 38.936$ years. Renewable energy is then used for a little less than 15 years (until $T_1 = 53.5668$) before direct R&D expenditure j becomes worthwhile. The renewable technology then reaches its ultimate frontier around 13 years later at $T_2 = 67.0686$ years.

Figure 9 shows the behavior of the main variables in the economy during the initial regime. Fossil fuel use leads to growth in consumption, as well as in the economy's capital stock. However, increasing investment in the development of mining technologies is necessary to meet demand as the economy grows. Towards the end of regime 1, the costs associated with increase fossil fuel use are large in real terms. This paves the way for the transition to the renewable energy regime.

Figure 10 shows the behavior of the main variables in the first renewable energy regime where technological progress continues to reduce renewable energy costs. Here, economic production is fueled through the use of renewable energy. Direct investment in renewable energy increases over time. Together with learning-by-doing, this leads to the accumulation of technical knowledge that is necessary for a more efficient use of this technology. Consumption and the economy's capital stock continue to grow. Ultimately, a technological limit is reached, beyond which there is no further decline in the cost of renewable energy.

[38] Of course, the learning-by-doing has the advantage that it directly contributes to output at the same time it is adding to knowledge.

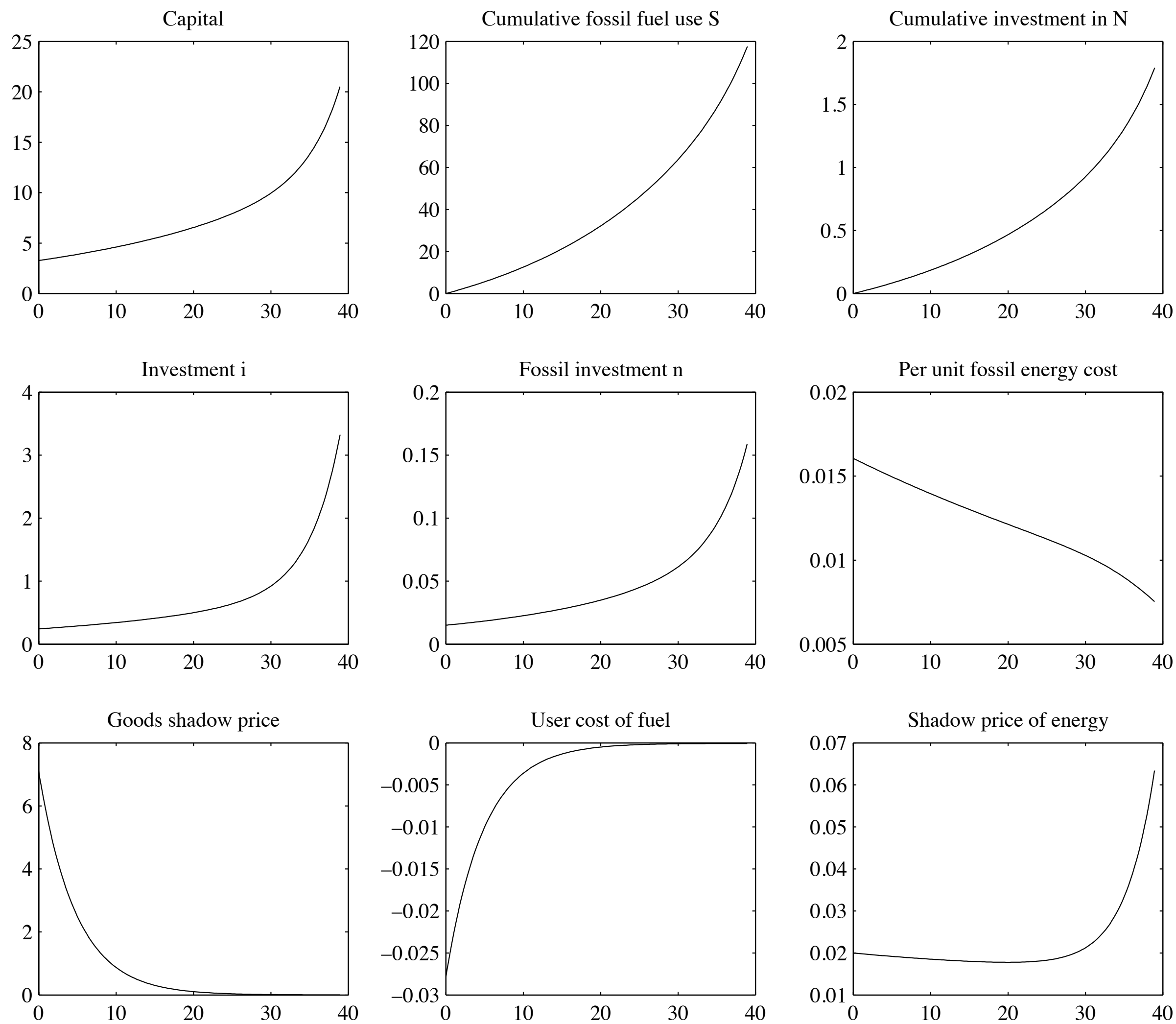

Figure 9: Fossil fuel regime without taxes or subsidies

4 Policy Scenarios

In this section we consider two alternative policies that could be used to accelerate the adoption of renewable energy in the economy. The first policy involves taxing investment in fossil fuel technologies. This policy should keep the costs of using fossil fuel high, leading to an acceleration of the adoption of the competing, renewable energy technology. The second policy is a direct subsidy to R&D expenditure in the renewable energy sector.

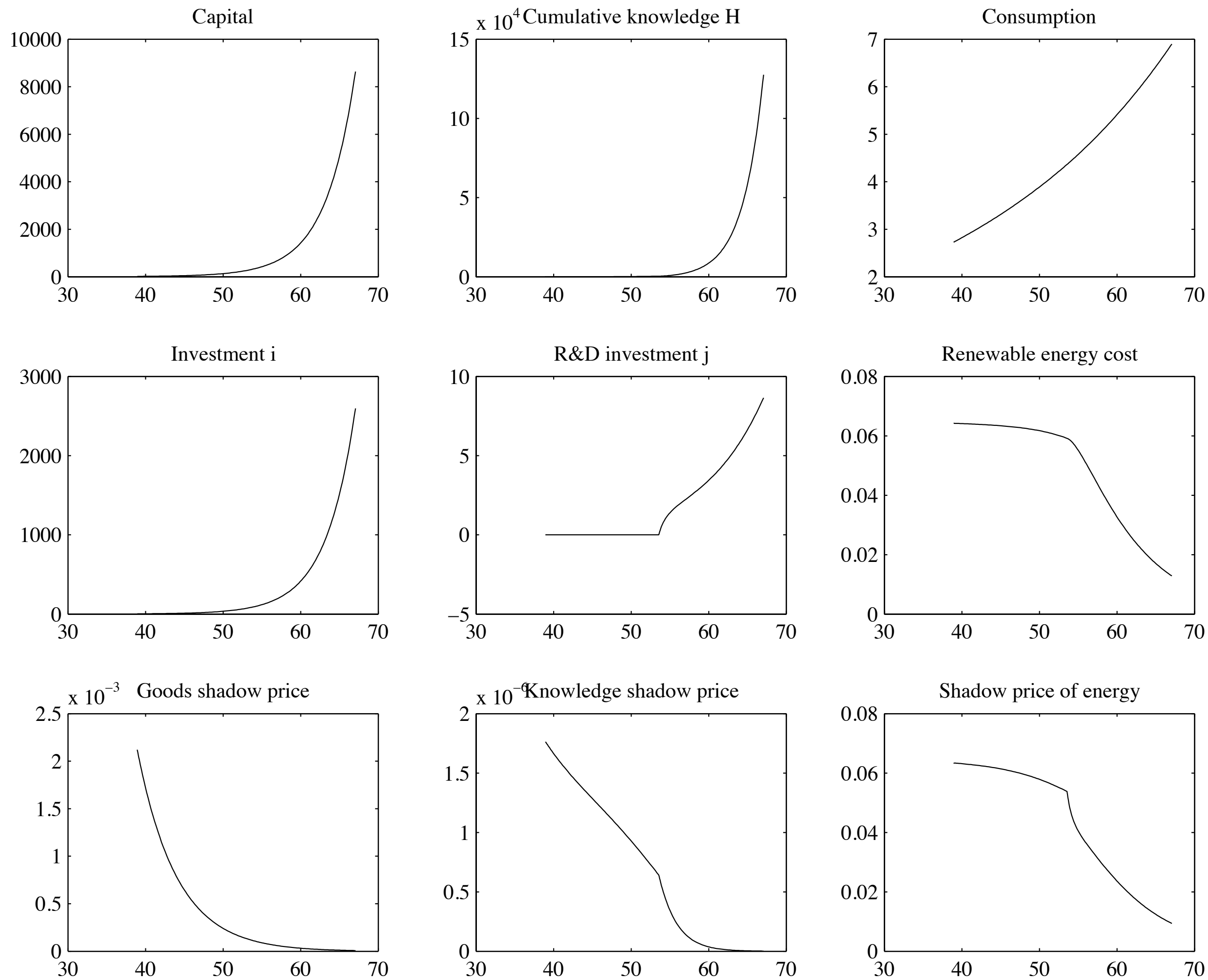

Figure 10: Renewable regime without taxes or subsidies

4.1 Scenario 1: Tax on Fossil Fuel Energy

One way of indirectly subsidizing renewable energy might involve imposing a tax on fossil fuels. Here, we consider different scenarios regarding the size of such a tax and explore the implications for renewable technology adoption and growth.

Introducing taxes on n during the fossil fuel regime, and returning the revenue to households in lump sum form, the budget constraint in that regime becomes:

$$c + i + n(1 + \tau_n) + g(S, N)R = y + T \tag{67}$$

with a corresponding budget constraint for the government given by:

$$\tau_n n = T \tag{68}$$

The revenue payment from the tax is lump sum in the sense that, when choosing investment in n, a private sector decision-maker takes account of the fact that higher n implies a higher tax liability, but T is taken as independent of any one individual's investment decision n. The budget constraint in regimes 2 and 3 is the same as before, so the analysis of those regimes remains unchanged.

The current value Hamiltonian and thus Lagrangian is now given by

$$\begin{aligned}\mathcal{H} =& \frac{c^{1-\gamma}}{1-\gamma} + \lambda\left[Ak + T - c - i - j - n(1+\tau_n) - g(S,N)R - (\Gamma_1 + H)^{-\alpha}B\right] \\ &+ \epsilon(R + B - Ak) + q(i - \delta k) + \eta B(1 + \psi j) + \sigma QR + \\ &\nu n + \mu j + \omega n + \xi R + \zeta B + \chi[{\Gamma_2}^{-1/\alpha} - \Gamma_1 - H]\end{aligned} \tag{69}$$

The first order conditions for a maximum with respect to the control variables are the same as previously except for n, which changes to:

$$\frac{\partial\mathcal{H}}{\partial n} = -\lambda(1+\tau_n) + \nu + \omega = 0, \omega n = 0, \omega \geq 0, n \geq 0 \tag{70}$$

The differential equations for the co-state variables remain as before. The shadow price of energy will again be

$$\epsilon = \lambda g(S,N) - \sigma Q \tag{71}$$

As before, we also assume parameter values and taxes are chosen so that investment in fossil fuel technology is productive, that is, $n > 0$. Then $\omega = 0$ and hence $\nu = \lambda(1+\tau_n)$, and, since $q = \lambda$, we have $\nu = q(1+\tau_n)$. But then using $\dot{q} = \dot{\lambda}$, and after substituting $R = Ak$, we now obtain

$$\left[\frac{\delta}{A} + g(S,N) - \frac{1}{(1+\tau_n)}\frac{\partial g}{\partial N}k - 1\right]\lambda = \sigma Q \tag{72}$$

Differentiating (72) with respect to time, substituting for $\dot{N}, \dot{\lambda}/\lambda = \dot{\nu}/\nu, \dot{S}, \dot{\sigma}$ and $\dot{Q} = \pi Q$, we obtain a condition relating the two types of investments (i and n) in the initial fossil fuel economy:

$$\lambda \left[\frac{\partial g}{\partial N} \left(n(1+\tau_n) + \delta k + \frac{\sigma Q A k}{\lambda} - i \right) - \frac{\partial^2 g}{\partial S \partial N} Q A k^2 - \frac{\partial^2 g}{\partial N^2} n k \right] = \sigma \pi Q (1 + \tau_n) \tag{73}$$

A second relationship between i and n is given by the budget constraint, which in this regime is:

$$c + i + n(1+\tau_n) + g(S,N)R = y + T \tag{74}$$

In equilibrium, however, the government budget constraint will imply that per capita lump sum transfers equal per capita tax revenue. Also, $y = Ak = R$ and $c = \lambda^{-1/\gamma}$, so (74) can be written as:

$$i + n = Ak(1 - g(S,N)) - \lambda^{-1/\gamma} \tag{75}$$

Substituting (75) into (73), we obtain a modified equation to be solved for energy technology investment n in the fossil fuel regime with taxes on such investment:

$$\begin{aligned} & n\lambda \left(\frac{\partial^2 g}{\partial N^2} k - (2+\tau_n) \frac{\partial g}{\partial N} \right) = \\ & \lambda \left[\frac{\partial g}{\partial N} [k(\delta + g(S,N)A - A + \frac{\sigma Q A}{\lambda}) + \lambda^{-1/\gamma}] - \frac{\partial^2 g}{\partial S \partial N} Q A k^2 \right] - (1+\tau_n)\sigma\pi Q \end{aligned} \tag{76}$$

Having obtained n, (75) determine i. The differential equations in the fossil fuel regime remain unchanged.

We consider different scenarios regarding the size of the tax. We summarize our findings in Table 1. The rows give the date of the transition to the renewable energy regime (T_1), the cumulative investment in fossil fuel technology at that time (N), the cumulative exploitation of fossil fuels before they are abandoned (S), and the date of transition to the final renewable energy regime (T_2). The first column gives the outcome in the absence of government intervention. The next two columns give the equilibrium values of the same variables when there is a 2 percent and a 4 percent tax on investment in fossil fuel technologies.

Table 1: Values of key variables with fossil fuel taxes

	$\tau_n = 0$	$\tau_n = 0.02$	$\tau_n = 0.05$	$\tau_n = 0.2$
T_1	51.2249	46.3859	45.19	39.9463
$N(T_1)$	64.6412	58.0567	57.5293	55.1507
$S(T_1)$	382.9009	350.9142	348.3918	334.1527
T_2	131.4168	126.5756	125.347	120.1413

These findings have a number of implications for policy. First, taxing fossil fuels accelerates the rate of adoption of the renewable energy technology. However, it is worth noting that the elasticity of the adoption rate appears to be small. A tax of 2 percent reduces T_0 by only 1.26 percent. On the other hand, the same 2 percent tax on n decreases the cumulative extraction of fossil fuel by 7.42 percent, and cumulative investment in fossil fuel technology at the switch date by 8.15 percent. That is, the tax causes fossil fuel reserves to be used less intensively in the fossil fuel economy in addition to accelerating the transition to renewable energy. This outcome comes at some cost. The distortion created by the tax creates a wedge between the equilibrium and the socially optimal level of investment. The capital stock at the time of the transition to renewable energy is 10.38 percent lower following the imposition of the 2 percent tax on n. More importantly, it can be shown that social welfare in the economy declines as a result of the tax.[39] Perhaps because the capital stock, and thus overall output, is lower under the tax, it takes longer before investment in renewable R&D becomes positive. It also takes longer before the economy reaches the stationary state where renewable technology attains its maximum feasible level of efficiency.

4.2 Scenario 2: Subsidy for Renewable Energy

We are again interested in how effective the subsidy is in both bringing forward the time of the transition to the renewable energy regime and also in reducing the total consumption of

[39] Absent any government intervention, the *First Welfare Theorem* holds in our model economy. If, as a result of externalities or other distortions the First welfare Theorem was to fail, then government policy could become beneficial.

fossil fuels before that time is reached. Introducing a subsidy on j during the regime where $j > 0$, the budget constraint in that regime becomes becomes:

$$c + i + j(1 - \tau_j) + pB = y - T \tag{77}$$

with a corresponding budget constraint for the government given by:

$$\tau_j j = T \tag{78}$$

Once again, the tax required to pay the subsidy is lump sum in the sense that individual decision-makers do not believe that their own choices of j will affect their per capita tax bill. The budget constraints in the fossil fuel regime, or when $j = 0$, are the same as before, so the analysis of those regimes remains unchanged.

The current value Hamiltonian and thus Lagrangian is now given by

$$\begin{aligned} \mathcal{H} = &\frac{c^{1-\gamma}}{1-\gamma} + \lambda \left[Ak - T - c - i - j(1-\tau_j) - n - g(S,N)R - (\Gamma_1 + H)^{-\alpha}B\right] \\ &+ \epsilon(R + B - Ak) + q(i - \delta k) + \eta B(1 + \psi j) + \sigma Q R \\ &+ \nu n + \mu j + \omega n + \xi R + \zeta B + \chi[{\Gamma_2}^{-1/\alpha} - \Gamma_1 - H] \end{aligned} \tag{79}$$

The first order conditions for a maximum with respect to the control variables once again are the same as before except for j where the condition changes to:

$$\frac{\partial \mathcal{H}}{\partial j} = -\lambda(1 - \tau_j) + \eta\psi B + \mu = 0; \mu j = 0, \mu \geq 0, j \geq 0 \tag{80}$$

The differential equations for the state and co-state variables remain as before.

Following the previous analysis, in regime 3 with $B = Ak > 0$ and $j > 0$, we will now have $q = \lambda = \eta\psi Ak/(1 - \tau_j)$, so the shadow price of energy becomes

$$\epsilon = \lambda(\Gamma_1 + H)^{-\alpha} - \frac{\lambda(1 + \psi j)(1 - \tau_j)}{\psi Ak} \tag{81}$$

Noting that $q = \lambda$ implies $\dot{q} = \dot{\lambda}$, we obtain

$$\frac{\dot{\lambda}}{\lambda} = \beta + \delta - A(1 - (\Gamma_1 + H)^{-\alpha}) - \frac{1 - \tau_j}{\psi k} - \frac{j(1 - \tau_j)}{k} \tag{82}$$

Differentiating $\lambda(1 - \tau_j) = \eta\psi Ak$ with respect to time, we obtain $(1 - \tau_j)\dot{\lambda} = \psi A(\dot{\eta}k + \eta\dot{k})$. Using (25), $\lambda(1 - \tau_j) = \eta\psi Ak$ and $\dot{k} = i - \delta k$, we obtain

$$\frac{\dot{\lambda}}{\lambda} = \beta - \delta - \frac{\alpha\psi(\Gamma_1 + H)^{-\alpha-1}(Ak)^2}{1 - \tau_j} + \frac{i}{k} \tag{83}$$

Equating (82) and (83), we obtain an expression involving the two investments i and j as a function of k and H

$$i + j(1 - \tau_j) = 2\delta k - \frac{1 - \tau_j}{\psi} - Ak(1 - (\Gamma_1 + H)^{-\alpha}) + \frac{\alpha\psi A^2 k^3 (\Gamma_1 + H)^{-\alpha-1}}{1 - \tau_j} \tag{84}$$

The budget constraint and the first order condition for c then provide a second equation:

$$i + j = Ak(1 - (\Gamma_1 + H)^{-\alpha}) - \lambda^{-1/\gamma} \tag{85}$$

where we have once again used the government budget constraint to eliminate the subsidy variable in equilibrium.

For $\tau_j \neq 0$, (85) and (84) can now be solved for j as a function of H, k and λ:

$$\tau_j j = 2k[A(1 - (\Gamma_1 + H)^{-\alpha}) - \delta] + \frac{1 - \tau_j}{\psi} - \lambda^{-1/\gamma} - \frac{\alpha\psi A^2 k^3 (\Gamma_1 + H)^{-\alpha-1}}{(1 - \tau_j)} \tag{86}$$

with i then given from (85). Observe that the higher the subsidy rate τ_j the more positive has to be the right hand side of (86). In turn, this will require a larger value of H for given values of k and λ. Not surprisingly, we conclude that a subsidy must increase investment in renewable technology knowledge H. With H higher, the transition times must also come earlier in time under the subsidy policy. Comparing (82) with (52), we also see that the renewable R&D subsidy will alter the differential equation governing the evolution of λ.

We also should note that, although the equations for the regime where $B = Ak > 0$ and $j = 0$ are not affected by the subsidy to j the transition to the regime with $j > 0$ will be affected. Specifically, the non-negativity constraint on j will now be binding where $\lambda(1 - \tau_j) = \eta\psi Ak$ rather than $\lambda = \eta\psi Ak$.

As with the tax policy, we consider different scenarios regarding the size of the subsidy. The first column in Table 2 remains unchanged as it gives the date of the transition to the renewable energy regime (T_1), the cumulative investment in fossil fuel extraction at that time (N), the cumulative exploitation of fossil fuels at that time (S), and the date of transition to the final renewable energy regime (T_2) in the absence of any government intervention. The next two columns give the equilibrium values of the same variables when there is a 2 percent, and a 4 percent subsidy on investment associated with renewable energy.

Table 2: Values of key variables with renewable investment subsidies

	$\tau_j = 0$	$\tau_j = 0.02$	$\tau_j = 0.05$	$\tau_j = 0.2$
T_1	51.2249	32.4124	24.0542	15.9956
$N(T_1)$	64.6412	87.1836	92.4245	110.4229
$S(T_1)$	382.9009	478.2624	498.5666	566.7097
T_2	131.4168	102.4820	90.0362	75.5973

These results contain some useful information for policy. First, a subsidy on investment in renewable energy accelerates the rate of adoption of the renewable energy technology. Indeed, although it is hard to compare the two directly, a renewable energy subsidy appears to be more effective than a tax on fossil fuels, with a 2 percent subsidy accelerating T_1 by 19 years. Another important difference with the previous tax scenario is that the fossil fuel reserves are used more intensively as a result of the subsidy. The intuition of this result is as follows. Since the adoption of renewable fuel is accelerated as a result of the subsidy, the opportunity cost of using fossil fuel in the short run declines. Thus, while the subsidy on renewables leads to a faster transition away from fossil fuels, it also implies a more intensive use of fossil fuel than what is socially optimal in the short run. While we do not model carbon dioxide or other emissions associated with the combustion of fossil fuels explicitly in our analysis, it is worth mentioning that this could imply an increase in such emissions in the short run.

5 Conclusion

Although economic policies affecting the energy sector have global consequences, such policies are rarely studied and evaluated using standard tools of macroeconomics. We built a model in this paper in which technological progress in renewable energy can be an engine of macroeconomic growth. The model includes three regimes: a world only using fossil fuels, a renewable-only world in which renewables are becoming cheaper, and a renewable-only world that has reached its maximum potential for technological development of energy sources. It takes into account investment, capital accumulation, and learning-by-doing. We calculated the equilibrium optimal path of investment in both the fossil fuel and the renewable energy sectors given existing global conditions. Finally, we studied the effects of levying taxes on the use of fossil fuel and providing government subsidies for renewable energy R&D.

As expected, we found that taxing fossil fuels accelerates the rate of adoption of the renewable energy technology. However, it is especially important to note is that the elasticity of the adoption rate is apparently small. In our model economy, a tax as high as 20 percent accelerates the renewable technology adoption by about 11 years, while a more modest 2 percent tax accelerates the transition by only five years. The tax does have the benefit of leading to a less intensive use of fossil fuels that should result in lower cumulative CO2 emissions. However, the distortion from the tax creates a wedge between the equilibrium and the socially optimal level of investment. Hence, welfare in the model-economy declines in proportion with the level of the tax.

In comparison with taxes, subsidies on renewable energy investment accelerate the rate of adoption of the renewable energy technology at a faster rate but also lead to the use of more cumulative fossil energy. A relatively small 2 percent subsidy accelerates the introduction of the renewable energy regime by 19 years, or nearly twice the effect of the 20 percent tax.

However, as a result of the renewable energy subsidy, the fossil fuel reserves are used more intensively in the short run. While somewhat paradoxical, the conclusion can be explained as follows: Renewable fuel will be used sooner due to the subsidy, so the opportunity cost of using fossil fuel in the short run declines. More fossil energy use is likely associated with more CO2 emissions and associated externalities, though we do not explicitly model emissions with the model.

Our analysis can be extended in many ways. Introducing technology-specific capital could allow us to more accurately capture the trade-off between fossil fuel and renewable energy production. Separating the effects of learning-by-doing and explicit investment in R&D would allow us to capture innovation and cost reduction in the supply of renewable energy in greater generality. Studying decentralized allocations will permit us to explicitly account for creative destruction and the possibility of under-investment in R&D. Finally, our current calibration could be modified to target the economy's initial capital stock. This would allow us to perform more meaningful welfare comparisons across different policy regimes. We believe that our main findings will remain qualitatively true under such extensions. We leave these issues to future research.

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