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Essays in Environmental and Energy Economics

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ABSTRACT

ESSAYS IN ENVIRONMENTAL AND ENERGY ECONOMICS

BY

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This dissertation consists of three separate chapters using theory, simulation, empirical techniques, and also an experiment to address several questions relating to utilizing fossil fuel-based energy and its consequences on environment and society.

My first essay, titled "Endogenous Population Growth in a Macro Environmental Model," simulated, based on U.S. calibrated data, the effect of utilizing clean energy vs. fossil fuel energy on long-run economic growth and its impact on the total welfare of the society. I present a dynamic growth model that explicitly allows for the interaction between an economy and an environment. I allow for endogenous population growth, where population is affected by living standards and level of industrialization as well as natural resources, indirectly through production. Endogenizing the population growth the growth rate of GDP per capita is lower under endogenous population scenario relative to exogenous population growth. Imposing carbon-tax element on the energy producers' profit would accelerate the adaptation of the clean

energy and sustain fossil fuel resources for a more extended period and would increase the individuals' long-term total consumption.

The second essay, titled "Having Skin in the Energy Game: The Impact of Social Norms on Energy Regime Changes." In this paper, I present a survey study in an experimental field context that explores the social norms effect on petition signing, focusing on clean energy adaptation instead of fossil fuel energy. I use multiple energy consumption data at the national level for selected countries. This research highlights that not only social norms could be compelling individuals' behavior, but also that they are sensitive to the types of information which are disclosed to them.

I develop my final essay, titled "Energy Fallout: Air Pollution Effects on Environmental and Social Externalities," estimated the effect of different types of energy consumption on mortality rates and violent crimes. This study aims to estimate a reduced-form model that could explain and then verify the possible relation between crime rates and mortality rates that arise from the different energy regimes utilization in affected regions, using mechanism effect analysis; while air pollution and level of income are two channels of this causation analysis.

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FARAZ FARHIDI

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ACCEPTANCE

This dissertation was prepared under the direction of Faraz Farhidi's Dissertation Committee. It has been approved and accepted by all members of that committee, and it has been accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Economics in the Andrew Young School of Policy Studies of Georgia State University.

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I could not have it made this far without the support of my family and friends. We have heard a version of this cliché phrase before; everything about the "thank you" process has become cliché. Even though, no matter how we use those letters, in this section, we want and need to thank those who without them, we would not be at this stage. Now, I try to create my cliché. These several sentences are the only part that no one needs to revise, or their comments are not needed; for sure, beside the hardworking fellas at writing center, specifically Nicole Turner, who without having them on board, no one, including myself, would understand a bit of this writing which people call a dissertation!

The irony is that I doubt anyone is going to read this part of my dissertation, except my wife. Previously, I have been accused of not mentioning her name in my master thesis, even though we had not been met at the time! But, complaints remain. So, thank you, my love, for being there always, or at least most of the time, for me. To tell the truth, who wants to live with a graduate student without a real job! Without any doubt, that is a first sacrifice she made.

I want to thank my mentors, here at Georgia State, Spencer Banzhaf, Paul Ferraro, Glenn Harrison, Bruce Kaufman, James Marton, Vjiollca Sadiraj, and specifically, John Gibson for all the head-aches I gave him. My exclusive acknowledgments to Garth Heutel, my advisor, who gave validity to my dissertation. I do not know how he could handle all the frictions I caused over the past two years; he must have iron nerves. I also want to thank our hardworking staff in the Economics department for their gracious help, especially Bess Blyler.

The way I see: life without a purpose is pointless. We may set different purposes for ourselves based on our realization, but at the end of the day, we want to find a way to help ourselves to be successful in the path to our purpose. To me, the best way to help ourselves is to help others. But to handle it, we need a vast source of energy. And what would be a better source than love and laughter? And who provides it? Family and friends. That is a reason, to me, the whole purpose of life and how we achieve it is summarized in family and friends. I know, without hesitation, I could not breathe a single moment without them. The sad news is, I cannot even repay my debt, which is my life, nor thank them enough. I can write a book on thanking all the people I owe, but it does not help the case! So, all I am able to do, here, is to say thanks to my parents, my sister and brother, my extended family and friends, and again and again my wife (my darling I named you twice hopefully now we can resolve the tragedy of my master thesis) and our expected son, who all together formed my family; and I am grateful to have such a family.

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I. Endogenous Population Growth in a Macro Environmental Model

Introduction

While the Industrial Revolution allowed for the development of new schemes of utilizing fossil fuel resources that ultimately lead to economic growth (Stern, 2011), there is solid evidence that devastating effects of climate change—due to the use of fossil fuel-based energy—will take place unless major actions are taken immediately to transform our fossil fuel-based energy system into a non-fossil fuel-based system (Schwartzman, 2008). Predicting the economy's future growth path—while taking into consideration the effects of the environmental degradation—is of the utmost importance. In this regard, there are often two overlooked issues in the macro environmental literature: Many macro models assume that population growth is exogenous and does not feedback on the environment. Second, most of the environmental approaches do not include the binding constraint of non-renewable resources into their model[1].

In this paper, I extend macro environmental framework by allowing for both non-renewable and renewable energy, and by endogenizing population growth, using both social planner and market-based approaches. The effect of population growth on economic activities is not clear based on different models and approaches. Hardin (1968) argues that to have a sustainable economy, population growth must be zero to keep our limited resources from being over-utilized. Meadows, et al. (1972) report that the Earth's industrial capacity and the population would catastrophically decline if we continue the level of capital accumulation that Turner (2007) and Hall & Day (2009) show. However, Grossman & Helpman (1991) and Aghion & Howitt (1998) claim that high population spurs technological change, which is the engine of

[1] Basically, there is no end point in their prediction.

economic growth (Romer, 1990; Jones, 2002). Building upon the existing endogenous population growth framework, I connect population growth with not only the living standards and level of industrialization but also with the adaptation of renewable energy resources. By solving the proposed model and making predictions based on the different energy adaptation scenarios, policy recommendations will be derived.

The main contribution of this work is: moving away from the exogenous population growth as in the existing climate models, adjusting the framework proposed in the endogenous population studies such as Cigno (1981), Ehrlich and Lui (1997), Nerlove and Rault (1997), and Krutilla and Reuveny (2006); and adding a resource binding constraint to create a tradeoff between renewable and non-renewable energies. The other contribution is to modify a new model for technological progress in which new technology is a function of existed technology, number of researchers, and investment. Financing new advancement in technology, which has been neglected from the previous works, is vital in the proposed setup. In the model, energy is the primary factor in the production process, the same as technological progress, labor forces, and physical capital. Stiglitz (1974) explores the implications of introducing exhaustible natural resources. In his model, natural resources can make the system unstable, as an essential factor of production. Hartwick (1977), Nordhaus (1996, 2008), Popp (2004), Hassler & Krusell (2012), Krusell et al. (2016) and Kummel (2016) present similar models in which energy is considered a primary factor of production and is used to identify the impact of resource constraints on economic activity and the environment. However, the energy itself can be substituted by any other source of renewable energy. In the model setup, there are binding constraints for the resources—following Acemoglu et al. (2012)—which limit growth.

The proposed model assumes that while population is important for the economy's growth path by providing labor force and researchers, it has an adverse impact on the economy due to the constraints of the environment and resources. As a result of endogenizing the population growth, while environmental erosion is included, the growth rate in the economy would be slower relative to the exogenous scenario. One of the reasons for such a different conclusion is that population leads to the economic growth through providing labor forces for the production process in both scenarios. In the endogenous case, however, there is feedback from environmental erosion on population, which diminishes the sources for future economic growth. Another important finding is that there would be a smooth transition in the economic activity during the adaptation of the production process that relies entirely on using renewable energy as a primary energy factor if the population is considered exogenous. Comparing two modified approaches to solve the model, I show that in the market-based method the firms utilize intensively more fossil fuel, relative to the social planner approach. The rate of clean energy adaptation would be lower relative to the centralized method. Considering nonlinear interactions between the elements in the environment (Dawson et al. 2010), using exhaustively fossil fuel-based energy leads to a more catastrophe complication in our ecosystem.

The paper is formatted as follows: The second section below reviews the existing literature which is connected to this research. Section three presents a theoretical model that can be used to verify the validity of the discussed questions in this research, with a following short section on solving the model and calibrating the parameters. Then, I propose a decentralized model, which is closer to the current market structure in the developed countries. In the fifth section, the results of the social planner solution will be discussed for both exogenous and endogenous population growth, as well as a comparison between two different methods will be examined. Lastly, I introduce two policy recommendations to the market-based approach and present a welfare analysis.

Literature Review

The existing literature in endogenous growth has focused on technology and rarely on population impacts, whereas the literature on environmental degradation, caused by utilizing fossil fuel energy, has relied mostly on exogenous technology and population growth as reviewed below. The scholarship has not yet studied a comprehensive model in which the often-discussed elements have been fully addressed. Recent endogenous growth models, such as AK[2], R&D, and Schumpeterian growth models, explicitly allow for optimizing the technological process. In those models, both innovation and capital accumulation can determine the long-run growth rate. In the long run, the stock of ideas is proportional to the worldwide research effort, which in turn is proportional to the total population of innovating countries (Jones, 2002). Acemoglu et al. (2012) introduce environmental constraints into a growth model with competing innovation applications. The fact that knowledge spillovers create positive externalities plays a crucial role in the ultimate cost of climate and technology policies (Fischer & Heutel, 2013).

Climate change engineered by human activity is a pure externality with global scope. The fossil-fuel use causes emissions of carbon dioxide into the atmosphere and results in global warming, thus imposing a cost that impacts not only all living humans but also future generations (Hassler & Krusell, 2012; Krusell et al. 2016). Mathiesen et al. (2011) reveal that utilizing renewable energy and more efficient conversion energy technologies can have positive

[2] AK model is one the first models which attempts to endogenize the economic growth by using a model in which output is a linear function of capital (Y=AK).

socioeconomic impacts and lead to a potentially higher rate of employment and earnings. Fully renewable energy systems will be technically achievable soon and can be economically beneficial, compared to current energy systems. Tahvonen and Salo (2001) believe that there would be a smooth shift from non-renewable to renewable resources, and it causes a drop in the future economic growth which is going to recover after some period. Sustainability of development depending on renewable resources has been confirmed by other researchers such as Li and Lofgren (2000) and Lund (2007).

Stiglitz (1974) explores the assumptions of introducing exhaustible natural resources, which can make a system unstable, as an essential factor of production with a constant rate of population growth. Later on, Kummel et al. (2002) present a more advanced model, called KLEC, in which the combination of capital, labor, energy, and creativity produces a final good. Nordhaus (1977, 1994, 2000, 2008, 2011), Golosov et al. (2012), and Hassler and Krusell (2012) have pioneered the area by building integrated assessment models (vastly known as DICE and RICE) expanding neoclassical growth models. They augmented essentially with a set of climate equations mapping atmospheric carbon into temperature and energy sectors, allowing people to expend costly resources to limit emissions from a given amount of use of fossil fuels. There exists another line of literature (employed by Bernstein et al. 1999, Rutherford et al. 2009, and others) that explores the impacts of climate policies on the energy market and economy using Multi-Sector, Multi-Region Trade (MS-MRT) based on computable general equilibrium method (CGE). But the role of population in all of the mentioned models has been neglected.

Ehrlich & Ehrlich (1990) claim there is an issue with overpopulation in a region relative to its resources and the ability of the environment to sustain human activities. Recent issues such as climate change, the global decline in population growth rate, and the recent economic downturn have prompted renewed concern about whether long-standing trajectories of the population and economic growth can continue (Brown et al. 2004). Meadows et al. (1972) state that the earth's industrial capacity and population would catastrophically decline if we continue the level of capital accumulation that Turner (2007) and Hall and Day (2009) show. Following Lee (1988), Kremer (1993) constructs an integrated model of population growth and technological change; the proposed empirical evidence supports his model that the growth rate of the world population has been proportional to the degree of population. These results are opposed by pioneering economists such as Becker and Barro (1989) and Acemoglu and Johnson (2007) who believe that population growth hurts income per capita.

Setting up a model of endogenous technological change that nests the Romer (1990) and the Jones (1995a) frameworks, Prettner (2013) considers the associated costs of having children involved in endogenous fertility decisions of households. He indicates that underlying demographic processes play a vital role in characterizing the R&D intensity and, therefore, affect long-run economic growth contexts of industrialized countries. Nerlove & Rault (1997) modified the 1956 Solow-Swan model by introducing a simple form of an endogenous population and showing that as income grows, fertility rate might not change because both birth and death rates fall, and physical and human capital per capita increase over time.

Cigno (1981) was the first to argue that the assumption of a constant rate of population growth is implausible in an economy constrained by exhaustible resources and examined the implications of making the population growth rate a function of consumption and capital per capita. Fanti and Manfredi (2003) build on Solow’s model and account for the continuation of a delay in the process of employment, due to the age structure of the population. They also utilize the existence of a Malthusian relation between wage and fertility, to generate stable fluctuating growth paths. An interesting consequence of the presence of the endogenous population in their model is that population growth may eventually promote economic growth. Later on, Krutilla and Reuveny (2006) evaluate the dynamic effects of incorporating an endogenous process for population growth into a renewable resource-based growth model. Their model is abstract in the Macroeconomics sense since there is no capital accumulation and production process. In their model, renewable energy is only used as a resource; thus, there is no trade-off between renewable and non-renewable resources. Moreover, they linked population to renewable resources where there is no limit on the non-renewable reserves. They, as did Stokey (1998) and Dasgupta and Maler (2000), reemphasize the urgency for the development of growth models that include both the environment and endogenous growth for human populations.

The models we have been discussing so far do not allow for the trade-off between non-renewable natural resources and renewable resources, or an endogeneity of population growth and technological progress. In the current research, to extend the environmental macro models, in the climate context such as DICE, my model specification includes endogenous population growth—based on the degree of industrialization and income level—as well as endogenous technological progress. As such, in the proposed framework, I am able to identify how endogenizing the model can affect the growth path of the economy, considering the environmental deterioration, and predict long-run growth with different types of energy resources. In addition, the model will be calibrated based on not only the U.S. data analysis but also the empirical estimation derived from previous work.

Model and Solution Method

In this section, first, I plan to build up the model in the following sub-section. Then, I am going to disclose how values have been assigned to different parameters. In the third and fourth sub-sections, the method to solve the model will be explained.

Constructing the model

There is a representative consumer in the model—consistent with the Ramsey-type models—with a utility function of a single commodity that is consumed at different points across time. The utility function includes a discounting factor to smooth consumption over time. The consumption good is delivered with an aggregate production function of technology, capital, labor, and energy, and it allows for the environmental degradation. Technological progress in clean energy, as well as the population growth, is endogenous in this model. Capital is accumulated in a standard Solow model, taking investment and consumption to be perfect substitutes.

- **Utility function**

The following model is a modified version of the Popp (2004) model[3], which is an extension of the DICE model itself by endogenizing the technological progress based on R&D models. I also endogenized population, according to the process in Cigno (1981). There is a possibility of making a model stochastic by adding exogenous shock to the technological progress and the new resource discoveries. In the proposed model, social planner maximizes the utility which is a

[3] I will use the discrete model excluding the population in utility function according to Hassler & Krusell (2012).

function of consumption per capita, (Eq. 1) subjects to the income constraint (Eq. 3), in an infinite horizon.

$$\underbrace{\mathrm{Max}}_{C_t, K_{t+1}, TY_t, FE_t} = E_0 \sum_{t=0}^{\infty} \beta^t U(c(t)) \tag{1}$$

$$U\big(c(t)\big) = \frac{c_t^{1-\sigma}}{1-\sigma}, \quad c_t = {}^{C_t}\!/_{L_t} \tag{2}$$

In the equations above, U_t represents utility at time t, C_t is the total consumption, c_t is per capita consumption, L_t represents the total labor force in the market, β is a discount factor to represent the rate of time preference, and σ is the parameter for the risk attitude of the agent.

- **Production allocation**

$$Y_t = C_t + K_{t+1} - (1-\delta)K_t + CEX_t FE_t + TY_t \tag{3}$$

Equation three shows the income allocation in which CEX (the cost of the providing of fossil-fuel energy[4]) is derived endogenously in the model. In the above setting, part of the income (TY) finances the technology for the clean energy (AC). C is the total consumption, K is the physical capital, and FE represents for non-renewable[5] energy.

$$Y_t = ED_t[A_t K_t^{\alpha} PL_t^{1-\alpha-\gamma} E_t^{\gamma}] \tag{4}$$

$$E_t = [(CE_t)^{\rho} + FE_t^{\rho}]^{1/\rho} \tag{5}$$

[4] This cost is not exactly equivalent to the cost of extraction in Stiglitz (1976), as it is argued in Appendix I.
[5] Or we can consider it as fossil fuel energy.

$$CE_t = AC_t * CE \quad (6)$$

$$ED_t = 1 - ({}^{FE_t}/_{\varphi})^{\vartheta} \quad (7)$$

Here, I included the energy as another primary factor of production (Y_t), as did Krusell (2016). A_t is the technological progress, PL_t is the fraction of the labor force who directly participates in the production process and E_t is the energy input required in the production process as a primary factor. ED_t is the environmental deterioration constraint (or damage function), as a decreasing function of the non-renewable energy consumption (FE_t). φ is the normalizing factor to keep the negative impact of FE_t on the production less than one. Energy is another primary factor of production such as technology, physical capital, and labor. A key aspect here is that non-renewable energy resources are finite, unlike DICE-RICE models in which the fossil fuel supply is treated as inexhaustible (Nordhaus & Boyer, 2000). However, the renewable resources, based on the availability of the technology, are infinite. CE is the total available stock of clean energy in an area ready to use. However, we can only use part of the energy, based on technological advances, AC_t, to utilize it. The variables and parameters are listed and explained in Appendix I.

- **Clean energy technology**

$$AC_{t+1} = AC_0 AC_t^{\theta} (TL_t TY_t)^{\omega} \quad (8)$$

Popp (2004) used an R&D based model (Jones, 1995) to endogenize the technological progress in his model. However, the production technology of the clean energy utilized here is the extended version of Jones (2002). Farhidi’s (2017) modification added TY, which is the required resources for financing the technology. TL is the effective research effort. AC_t is the required technology to utilize clean energy such as solar and wind. The economy consists of two types of labor: the researcher who produces a new idea, and the laborers who produce the final good as an output.

- **Fossil fuel price**

$$CEX_t = P_0 + P_1\left(\sum_{i=1}^{t} FE_i \Big/ \overline{FE}\right)^{P_2} + P_3\left(FE_t \Big/ \overline{CTE}\right)^{P_4} \qquad \sum_{i=1}^{t} FE_i \leq \overline{FE} \qquad (9)$$

Following the idea in Popp (2004), the cost of extraction of the fossil fuel energy (CEX) is the sum of the marginal cost of fuel extraction and a markup, which includes any transaction costs according to Equation 9, in which $\overline{FE}$ is the total fossil fuel available to extract, and it is provided by nature. P_1 represents changes in marginal cost as the extraction changes, and P_2 shows the impact of the ratio of fossil fuel accumulation on the price level. Unlike the Popp's model, there is no maximum in this pricing strategy, which equals to $P_0 + P_1$, in the last period; however, fossil fuel price increases intensively in the later periods due to the last added element $(P_3(FE_i / \overline{CTE})^{P_4})$ to the price function in this setup. This extra factor has been added, compared to the Popp's model, to penalize fossil fuel consumers and unforeseen conflict shocks via price increment in future.

- **Population growth**

$$A_{t+1} = (1 + \overline{A})A_t \qquad (10)$$[6]

[6] We can also consider the technological progress stochastic in the production process to capture any possible fluctuation later.

$$PL_t + TL_t = L_t \quad (11)$$

$$l_{PL} = \frac{PL_t}{L_t} \text{ and } l_{TL} = \frac{TL_t}{L_t} \quad (12)\ \&\ (13)$$

Technological progress for the production process (At) is considered exogenous. For labor force participation, we need to define two ratios (l_{PL} and l_{TL}), which are assumed to be constant over time; therefore, the distribution of the labor force does not change between two different sectors, which are shown in Equations 12 and 13.

$$L_{t+1} = (1 + \bar{L})L_t \quad \text{(If the population grows exogenously)} \quad (14)$$

$$L_{t+1} = L_t + L_0\left({}^{Y_t}/_{L_t}\right)^{\varepsilon_1}\left({}^{L_t}/_{K_t}\right)^{\varepsilon_2} \quad \text{(If the population grows endogenously)} \quad (15)$$

L_t is the level of population[7] in an economy. The main distinction of the presented model is built as follows. I endogenized the population growth which is directly retrieved from Cigno's (1981) model[8] by linking it to the environmental degradation through production; therefore, the constant population growth in Equation 14 ($\bar{L}$) was replaced by the setup in Equation 15. Therefore, I use Equation 14 for the first specification of the model in which population grows exogenously. Then I used Equation 15 in the other model specification.

It must be noted that income plays an important role in population growth. Fertility theories proposed by Becker (Becker 1973; Becker et al. 1994) highlight the indirect influence of living standards within this framework. L_0 can be derived exogenously by the fact that population is a

[7] Population refers to the labor force in the current setup, not the total population of an economy
[8] Krutilla & Reuveny (2006) link the population only to renewable resources since their model does not include production process, capital accumulation, and non-renewable resources.

biological factor that grows exponentially. But, because of industrialization, the nature of this growth has varied over time. The rate of population growth is positively related to per capita consumption and inversely related to the degree of industrialization[9]. There are five choice variables in this model: physical capital (K), fossil fuel energy (FE), utilizing the clean energy (AC), required resources for financing the clean technology (TY), and the consumption (C).

Data Calibration

To calibrate the model's parameters, I assigned the previously used values (in the literature) to the parameters, and I estimated the ones with no existing values, using real data. I used data from 1990-2012, mostly retrieved from the World Bank Data Center, for the different indices to calibrate the parameters using time series analysis for the U.S. only. I also used environmental bio-capacity[10]—retrieved from the Global Footprint Network database—as a proxy for the environmental degradation. For the total energy (E_t), I included the country's total energy use, and then I used renewable energy consumption as a percentage of total energy consumption to calculate FE_t and CE_t (as a proxy to get the required technology for utilizing the clean energy). More specifically, I used GDP inflation-adjusted for the total production, total gross capital inflation-adjusted using capital formation index, and calculating technological progress (A_t), using methods developed in World Bank's 2008 report. World Bank provides the data for the total population, labor force participation, and the number of researchers in the R&D sector, the

[9] Degree of industrialization is the capital-labor ratio. Based on Cigno (1981), industrialization and its concomitant, urbanization, have impacts on birth rates which is consistent with the intertemporal utility maximization. It is also consistent with the empirical observation that at low levels of industrialization the rate of population growth tends to move in the same direction as per capita consumption, while at high levels of industrialization it tends to move in the opposite direction.

[10] The bio-capacity has risen as one of the world's dominant measures of human demands on nature. It permits us to compute human pressure on the environment (e.g. if everyone lives the lifestyle of the average American, we would need at least four more planets). Environmental biocapacity thus focuses on whether the planet can keep up with our growing demands.

latter index utilized as a proxy for the number of researchers in clean energy production. For the technological progress for the clean energy, I used the total R&D spending in the U.S. as a proxy.

For the value of β from the first equation, $\text{Max}\,W = \sum_{t=0}^{T} \beta^t U(c(t))$, I used 0.96 for the yearly discount factor, which is commonly used in growth models. σ, the level of risk aversion in Equation 2, $U\big(c(t)\big) = \frac{c_t^{1-\sigma}}{1-\sigma}$, is equal to 2. A higher (lower) value of σ corresponds to more (less) risk-averse agents can be used as well. Using the basic calibration from Krusell (2012), I used the parameters for Equation 4 $\{Y_t = \mu_t[A_t K_t^{\alpha} PL_t^{1-\alpha-\gamma} E_t^{\gamma}]\}$ as follows: $\alpha = 0.27$, $\gamma = 0.04$.

I set the parameter ρ to 0.5 based on Popp's (2004) model. To estimate the Equation 8 parameters ($CEX_t = P_0 + P_1(\sum_{i=1}^{t} FE_i / \overline{FE})^{P_2} + P_3(FE_t / \overline{CTE})^{P_4}$), I used the same values which are: P0=276.29, P1=700, and P2=4. According to Popp (2004) [as in RICE model], I then scale P0 and P1 by dividing them by hundred to fit into my calibration. Then I assign 3.5 to P3 and 0.9 to P4 to better capture the price intensity in the future. To estimate the rest of the parameters, I used time series analysis which is fully explained in Appendix I (using Equations (B1), (B2) & (B4) in Appendix I). The summary of all of the calibrations is shown in Table (1). I did not take care of any possible endogeneity in the estimation since the primary reason of doing that is to find the benchmark for the non-existence parameters, not to derive the exact values which are out of the scope of this study.

Solving the Growth Path (Exogenous population vs. endogenous)

To solve the model, first we can simplify the constraints by substituting Equation 6 into 5, and then substitute back the new equation (total energy production) and 8 (environmental degradation) into the production function (Eq. 4), yielding Equation C1 (in Appendix I). Then, we substitute the modified production function and the price for fossil fuel energy (Eq. 9) into the income allocation function (Eq. 3) to get Equation C2. Then, substitute Equations 12 and 13 into C1 and 8, respectively, for PL and TL, to get the two constraints (Equations C3 and C4) for the Lagrangian. Now we can establish the Lagrangian, in which households are maximizing their utility over infinite time, for the base model in which the population growth is exogenous.

$$\mathcal{L} = E_0 \sum_{C_t,FE_t,TY_t,K_{t+1},AC_{t+1}}^{t:1\to\infty} \Bigg[\beta^t \frac{{C_t/L_t}^{1-\sigma}}{1-\sigma} + \lambda_{1t} \Bigg\{ \left(1 - \frac{FE_t}{\varphi}^{\vartheta}\right) (A_t K_t^{\alpha} (l_{PL} L_t)^{1-\alpha-\gamma}) \left((AC_t CE)^{\rho} + FE_t^{\rho}\right)^{\gamma/\rho} - C_t - K_{t+1} + (1-\delta)K_t - \left(P_0 + P_1 \left(\sum_{i=1}^{t} FE_i \Big/ FE_0\right)^{P_2}\right) FE_t - TY_t \Bigg\} + \lambda_{2t}\left\{AC_0 AC_t^{\theta} (l_{PL} L_t TY_t)^{\omega} - AC_{t+1}\right\} + \lambda_{3t}\{(1+\bar{L})L_t - L_{t+1}\} + \lambda_{4t}\{(1+\bar{A})A_t - A_{t+1}\} + \lambda_{5t}\{\overline{FE} - \sum_{i=1}^{t} FE_i\} \Bigg] \quad (16)$$

There are four choice variables in the above functional setup: level of consumption, capital investment, investment in the technology of renewable energy resources, and the amount of fossil-fuel energy. The total stock of fossil-fuel is constant and a given. Solving the first-order conditions (F.O.Cs), we get the Euler equations from the F.O.Cs. The solving process is shown in Appendix I.

Considering the three equations for income allocation (Eq. 3), production (Eq. 4)[11], and technological production for renewable energy (Eq. 8), and the Euler equations (Eq. C10, C11, C12, C13&C14), derived from the F.O.Cs, I can solve for this path using the actual values of the

[11] In which total energy consumption (Eq. 5) and environmental degradation (Eq. 7) are included

variables for the initial year (t=0)—which are shown in Table (2)—and then update the variables based on the above equations. Therefore, I directly use the law of motions (by forward iteration)[12] to obtain next period values based on the previously driven values. Thus, there is an implicit uncertainty about the ending period of fossil fuel energy at the starting point[13]. To select these values, I use 2012 as a reference year, extracted the values for the U.S., and then normalize it by million. The amount of clean energy is set to be 8% of the total energy consumption.

The only issue we have to derive the growth path, using the law of motions is to define the value of C_0 which is demonstrated in the footnote[14]. Having the above values as initial conditions (and defining C_0 as it has been explained), we can compute the level of production from Equation 4, the next period required technology for the clean energy from Equation 8, and the cost of extracting the fossil fuel (CEX) from Equation 9. Now, utilizing the budget constraint (Equation 3), we can calculate the next period physical capital (K_{t+1}), knowing all values for the

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[12] While it seems it might be the first time that the current method of using the decision rules—instead of value function iteration—(by using the initial values and Euler equations) has been applied, it has been discussed in some cases such as DICE user manual, computational and algorithm aspects, by Nordhaus & Sctorc (2013). The main reason that allows me to use the law of motions (for capital, fossil fuel energy and so on) is the exogenous equation for the cost of fossil fuel extraction. This extra equation helps me to construct the matrix of the law of motions, which depend on each other, and solve them all simultaneously.

[13] Alternatively, I can guess the end period for running out of fossil fuel energy, and iterate it back to the initial point. Then, I can do the same process for different ending points to get the highest given utility, and compare the new results to the current ones.

[14] Since the understanding of solving this model might seem a bit confusing, alternatively, I can explain a simple Ramsey scenario (for a discrete time) in which environment, endogenous technology and population, and energy are dropped. Therefore, our Lagrangian gets the following form: $\mathcal{L} = E_0 \sum_{C_t, K_{t+1}}^{t=1 \to T} [\beta^t \frac{{C_t/L_t}^{1-\sigma}}{1-\sigma} + \lambda_t\{Y_t - C_t - K_{t+1} + (1-\delta)K_t\}$. Solving the F.O.C we get: $C_{t+1} = C_t \left[(\beta[f'(K_{t+1}) + 1 - \delta])^{1/\sigma}(1+\bar{L})^{\sigma - 1/\sigma}\right]$. Now, to find the consumption path using my approach, we need the initial conditions such as C_0, K_0 and L_0. Since we cannot assign an initial value to C_0, we use the following procedure, just to derive the initial value for consumption, and then use the explained procedure in the main text to drive the growth path. We define a range of possible K_1 based on K_0 such as $0.5K_0 < K_1 < 1.5K_0$. Then, split the range into 100 possible values for K_1 and compute the corresponding utility for each of them. The one which maximizes the utility (of the household) would be our "K_1." Then, we can use the budget constraint to derive C_0. After that, we can use the formula for intertemporal consumption, to derive next period consumption and physical capital. Alternatively, we can derive the initial values using the steady state. Simply, set C_{t+1}, and K_{t+1} equal to C_t and K_t, and assign the values of C_{ss} and K_{ss} as the initial conditions. Having those we are able to derive the pathways for both consumption and physical capital by using the formula for the law of motion for consumption and budget constraint.

current (t=0) state. Now, we can update the labor force using Equation 14 for the exogenous case. The next period technological progress in the production process (A) can be achieved from Equation 10. Therefore, we can use Equation C12 to get the required fossil fuel energy (FE) for the next period. At this time, we can use Equation C10 (intertemporal consumption decision) to compute the level of consumption for the next period as well. Now, the only unknown variable for the next period would be the required resources for financing the clean energy technology (TY). Using the last Euler Equation C13, we can calculate the amount of this element. Repeating the same process, we can update all values for each period moving forward.

It must be noted that the approach I develop in this study is not a standard computational method. A social planner is not predicting the growth path. The planner maximizes the utility each period due to the existing, present resources. Therefore, the backward induction method has not been used since the exact time of depletion of natural resources is unknown. This form of set up is the real uncertainty of the model, implicitly implemented in the solving process. However, the issue of the discoveries uncertainty or the exact time of running out of fossil fuel, in the starting point, has not been studied explicitly within this framework since the current setup is deterministic, not stochastic. It is also worth mentioning that the social planner does not account for the nonrenewable resources constraint in the optimization problem in the beginning but tries to deal with it while there are not enough resources left to utilize. The main reason I use a non-conventional method to solve this model is that the ideology of this research is built on. There is no end time for resources (fossil fuel can be replaced by renewable energy); thus, the values of the transversality conditions for both physical capital and investment on renewable energy are unknown. The proposed approach does not sound quite appealing, but it saves the day.

To solve the model for the endogenous population case, we need to change the last constraint of the Lagrangian by substituting Equation 14 to 15. Therefore, we can rearrange the equation and substitute the production function (Equation 4), and Equation 11 to get the below equation:

$$L_{t+1} = L_0\left(1-\frac{FE_t{}^{\vartheta}}{\varphi}\right)^{\varepsilon_1} A_t^{\varepsilon_1} K_t^{\alpha\varepsilon_1-\varepsilon_2} l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma} L_t^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma\varepsilon_1/\rho} + L_t \quad (17)$$

Changing the third constraint (equation above), we can set our updated Lagrangian for the endogenous population growth:

$$\mathcal{L} = E_0 \sum_{C_t,L_{t+1},FE_t,TY_t,K_{t+1},AC_{t+1}} [\beta^t \frac{{C_t/L_t}^{1-\sigma}}{1-\sigma} + \lambda_{1t}\left\{\left(1-\frac{FE_t{}^{\vartheta}}{\varphi}\right)(A_tK_t^{\alpha}(l_{PL}L_t)^{1-\alpha-\gamma})\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma/\rho} - C_t - K_{t+1} + (1-\delta)K_t - \left(P_0 + P_1\left(\sum_{i=1}^{t} FE_i/\overline{FE}\right)^{P_2}\right)FE_t - TY_t\right\} + \lambda_{2t}\{AC_0AC_t^{\theta}(l_{TL}L_tTY_t)^{\omega} - AC_{t+1}\} + \lambda_{3t}\left\{L_0\left(1-\frac{FE_t{}^{\vartheta}}{\varphi}\right)^{\varepsilon_1} A_t^{\varepsilon_1}K_t^{\alpha\varepsilon_1-\varepsilon_2} l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma} L_t^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma\varepsilon_1/\rho} + L_t - L_{t+1}\right\} + \lambda_{4t}\{(1+\overline{A})A_t - A_{t+1}\} + \lambda_{5t}\{\overline{FE} - \sum_{i=1}^{t} FE_i\}] \quad (18)$$

Solving the first-order conditions, I can follow the same process as it has been done for the previous case to derive the Euler equations. Deriving the first-order conditions in the endogenous model is shown in Appendix I. Having the Euler equations beside the constraints, I am able to follow the same process in the exogenous population scenario to update the next period values with some minor adjustments. First, I am going to use Equation 15 instead of 14 to update the next year's total labor force. And second, I need to solve Equations C25, C27, and C28 simultaneously to get the next period values for C, FE, and TY.

Market-based analysis

In this section, I plan to develop the decentralized approach based on Golosov et al. (2014). The distinction between the current model and the previous one is that firms pick the optimal level of both types of energy, and households receive a potential profit from their dividend in the energy sector. While individuals rent their physical capital, firms decide what share needs to go to the production of final good, and which needs to invest in developing the required technology for producing clean energy. In the market-based approach, firms do not fully internalize the negative externalities risen from extracting and utilizing fossil fuel energy, as is the case in social planner framework.

Therefore, based on the deviation of the results in the market-based approach from the social planner, I can introduce a cost element—such as carbon tax—which would be included in the firms' profit function to capture negative externalities arising from environmental degradation. And in the next step, I can use this tax to finance the clean energy production, directly, without introducing the government section to see if the results converge with the social planner approach. If it does, I can propose a policy to promote the market approach analysis to mitigate the environmental problems in selecting the fossil fuel energy, without entering the government directly into the model.

Households

There is one representative household[15] for the whole economy who optimizes her utility based on her per capita consumption[16] bundle, subject to budget constraint 26:

$$\underbrace{\text{Max}}_{C_t, K_{t+1}} = E_0 \sum_{t=0}^{\infty} \beta^t \frac{c_t^{1-\sigma}}{1-\sigma} \qquad c_t = {C_t}/{L_t} \qquad (19\&20)$$

$$C_t + K_{t+1} = w_t L_t + (1 + r_t) K_t + \pi_t \qquad (21)$$

In the above equation, w_t is the labor's wage, and π_t is the gained profit from energy sector. Wage is the same across all sectors of the economy, which is perfectly mobile and substitutable labor. An individual can engage in two different sectors of the economy: in producing final good Y as PL; or, in developing new technology (AC) for producing clean energy. Either way, she earns the same compensation; therefore, I did not make any distinction in this section, but the firms can choose the final number. The household also compensates from renting her capital (K) to the market. She might receive some profit (π) from energy production sector as well.

Populations grow according to equations, which has been developed in the social planner approach. We can think about the fertility model in which households are choosing the next period population based on the income level and the industrialization intensity in an economy.

$$L_{t+1} = (1 + \bar{L}) L_t \qquad \text{(If the population grows exogenously)} \qquad (22)$$

$$L_{t+1} = L_t + L_0 ({Y_t}/{L_t})^{\varepsilon_1} ({L_t}/{K_t})^{\varepsilon_2} \qquad \text{(If the population grows endogenously)} \qquad (23)$$

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[15] One can think of the continuum of households who are identical in any aspect and characteristics.
[16] To be consistent to the social planner approach, per capita consumption has been considered.

Final good producers

There are two types of firms in our setup: the firms who produce final good (Y)—in the perfectly competitive market—for the consumption given the production frontier, and the intermediary firms who provide two types of energy (fossil fuel-based and clean energy) in which they may earn a positive profit. Since all the firms in each sector are identical with the same production frontier, for simplification in the model, we can assume there is a single firm in each category.

$$Y_t = ED[A_t KY_t^{\alpha} PL_t^{1-\alpha-\gamma} (CE_t^{\rho} + FE_t^{\rho})^{\gamma/\rho}] \tag{24}$$

$$E_t = [CE_t^{\rho} + FE_t^{\rho}]^{1/\rho}$$

The final good producers are solving their profit maximization by:

$$\underbrace{\text{Max}}_{KY_t, PL_t, CE_t, FE_t} \; EDA_t KY_t^{\alpha} PL_t^{1-\alpha-\gamma} \left(CE_t^{\rho} + FE_t^{\rho}\right)^{\gamma/\rho} - w_t PL_t - (r_t + \delta) KY_t - P_{FEt} FE_t - P_{CEt} CE_t \tag{25}$$

In which P_{FE} is the price of fossil fuel energy, and P_{CE} is the price of clean energy. Damage function is also included to the production function, to be consistent to the planner approach for the comparability; however, the costs of pollution are not fully internalized by firms since ED is constant and does not depend on the rate of extraction of fossil fuel.

Energy producers

In this sector, the firms are producing energy subject to the below optimization process:

$$\underbrace{\text{Max}}_{TY_t, TL_t, AC_t, FE_t} \quad \beta^t \pi_t \tag{26}$$

in which $\pi_t = P_{FEt}FE_t + P_{CEt}CE_t - w_t TL_t - r_t TY_t - CEX_t FE_t$ (27)

$AC_{t+1} = AC_0 AC_t^{\theta}(TL_t TY_t)^{\omega}$ in which $CE_t = CE * AC_t$ (28 & 29)

To derive the cost of extraction of fossil fuel-based energy, we can use the previous setup from Equation 9. The rest of the equations—for the technological progress and the population—are the same as the planner problem [(10), (11), (12) and (13)].

Solving the model

To solve this model, I plan to take advantage of the same framework that I have used in the social planner approach. Therefore, I am going to set up the Lagrangians for the household, as are shown in Equation 30 and 31, and then solve the F.O.C.s for all the sectors (in Appendix I). Having the Euler equations, along with the initial and market clearing conditions, I am able to set up the dynamic system of equations to derive the growth paths for the desirable variables.

$$\mathcal{L} = E_0 \sum_{C_t, K_{t+1}, L_{t+1}}^{t:1\to\infty} \Bigg[\beta^t \frac{{C_t/L_t}^{1-\sigma}}{1-\sigma} + \lambda_{1t}\{Y_t - C_t - K_{t+1} + w_t L_t + (1 + r_t)K_t + \pi_t\} +$$

$$\lambda_{2t}\{(1 + \bar{L})L_t - L_{t+1}\} \Bigg] \quad \text{(Population is exogenous)} \tag{30}$$

$$\mathcal{L} = E_0 \sum_{C_t,K_{t+1},L_{t+1}}^{t:1\to\infty} \left[\beta^t \frac{{C_t/L_t}^{1-\sigma}}{1-\sigma} + \lambda_{1t}\{Y_t - C_t - K_{t+1} + w_t L_t + (1+r_t)K_t + \pi_t\} + \right.$$

$$\left. \lambda_{2t}\left\{L_t + L_0({}^{Y_t}/_{L_t})^{\varepsilon_1}({}^{L_t}/_{K_t})^{\varepsilon_2} - L_{t+1}\right\}\right] \quad \text{(Population is endogenous)} \qquad (31)$$

It is worth arguing that once firms do not fully internalize the negative externalities, the results in both social planner and market-based approaches are going to be different, as a fundamental distinction between the first best approach (social planner) and second best approach (market-based). There are also, at least, two other distinctions across these two setups. First, social planner chooses the optimal level of fossil fuel in each period; however households do not have that choice; firms select that level based on their expected profit, while there is no such a profit in social planner method. Second, households rent the total capital and earn interest rate, and then, firms decide what portion of that should be spent in clean energy, and what fraction should be invested in physical capital based on their optimality conditions. Whereas, in the other framework, social planner choose how much she should invest in physical capital and how much in clean energy. Thus, it is not the same process in decision making. As a result of these differences, one can see the law of motion for consumption in planner solution (Equation C34) is entirely different from the one in the decentralized model (Equation C25). Therefore, the F.O.C.s and results should not be identical in both cases, fundamentally and computationally.

Results and Discussion

In this section, first, I am going to compare different exogenous growth rates in both social planner and market-based frameworks. Then I plan to analyze the exogenous growth scenario to the endogenous one.

Social planner solution (different exogenous growth rates)

The results are shown in Figure 1 when population grows exogenously with two different scenarios. In the first case, population grows by 0.02 percent every year. In the second, it increases by 0.6 percent per year, and it matches US population growth to some extent. We can see this difference affects the economic growth per capita slightly, and it changes the level of utilization of fossil fuel energy (higher for the higher growth rate in population). Higher rate of population growth means more laborers and researchers, therefore, more primary factors of production. However, more resources are needed to be utilized as well. While an economy produces more—and consequently, needs more energy and fossil fuel to use—in the higher population scenario, the economic growth per capita would be marginally lower because of the same argument. Therefore, not only with a higher rate of population, we do not experience a higher per capita growth rate in an economy, but also we spend more fossil fuel energy and degrade the environment more intensively.

Social planner solution (exogenous versus endogenous growth)

The results are depicted in Figure 2. Assuming the population adjusts itself through income and level of industrialization—given the endogenous population growth that is shown by the redlines in Figure 2—the economic growth per capita[17] would be slightly lower compared to the exogenous scenario, while population growth across two models are in the same range. The capital increases in both cases, but at a higher rate, after several periods, if the population grows exogenously.

[17] In another attempt in Appendix I, to better match the projected growth with the U.S. data over the next decades, I changed the capital share and reported the results.

I can argue that by the time we are running out of the fossil-fuel energy, the production process adapts itself, entirely using renewable energy as a primary energy factor[18] (therefore, there would be no delay in energy provision). While this transition does not affect the economy in this setup since there would be no consecutive adverse impact of fossil fuel utilization on the production process. Thus, a negative impulse from transforming to the full utilization of clean energy would be neutralized by a positive inclination of not having negative externalities in the economy.

Figure 2 shows us that if the population is considered exogenous, we conserve fossil fuel for a longer period, and utilize it less intensively compared to the endogenous scenario. If the population is tied to the income and level of industrialization, we utilize more fossil fuels and deplete non-renewable resources in a shorter time period.

Market-based solution (exogenous versus endogenous growth)

The results are depicted in Figure 3. The capital accumulation is higher in the exogenous scenario, as well as economic growth per capita. It is shown in Figure 3 that if the population is considered exogenous, we conserve fossil fuel for a shorter duration, and it reaches the maximum point of utilization sooner than in the endogenous scenario. If the population is tied to the income and level of industrialization, we utilize fewer fossil fuels and deplete non-renewable resources in a more extended period. The result of fossil fuel utilization contradicts the previous comparison in the social planner approach. However, the economic growth per capita is higher in the exogenous scenario compared to the endogenous scenario.

[18] It might be a case, here, that dropping in provision of energy—at the time of running out of fossil fuel—would be offset by cutting the negative externalities from production process.

Planner's problem vs. decentralized model (endogenous population)

Solving the model, the results show that the economy per capita would grow at a slightly lower rate (around 0.07 percent yearly difference on average) in a centralized model relative to the decentralized model while population grows with a lower rate (around 0.05 percent on average in one hundred and eighty periods) in the latter framework; but, ultimately, the economic growth per capita in both frameworks converge to the same amount. The firms accumulate more capital and invest less in clean energy in the market-based solution compared to the social planner approach. Also, the return on physical capital is higher than the return on energy in the production function and makes it more attractive for firms to invest in the capital, not the clean energy.

As is shown in Figure 4, in the planner's solution, the fossil fuel resources would have been exhausted at a slower rate, and there would be a higher rate of adaptation of clean energy relative to the decentralized model. Despite the higher rate of energy consumption, the economic growth per capita is higher in the market-based solution because firms invest more on physical capital and use more fossil fuel compared to the planner who conserves fossil fuel for a longer period, and also the economy experiences a lower population growth rate in the decentralized model. The reason might be clear since firms do not adequately account for negative externalities that arise from non-renewable resource utilization. The other finding is that the population[19] grows at a slightly higher rate in the planner's solution compared to the decentralized model, in earlier periods. With the current parameterization, population growth does not match existing rates in

[19] One would question that the depicted population is not realistic for the U.S. In Appendix I, I argue such issues.

the United States. However, in another attempt, I capture the current trend in population growth using alternative calibration for Equation 15 (endogenous population growth).

Policy implication

In this section, I try to investigate the situations in which the government imposes a regulation to converge the results in the market-based approach with the social planner approach in regard to the clean energy adaptation. An intervening party can set a rule in which every year a certain percentage of the total income needs to finance the production of clean energy without any direct interference from the government, so there is no need to enter the government spending and budget into the model. To do that, I can simply utilize the following assignment in which financing the clean energy (TY) is not a choice variable as it was in the previous setup; instead, it is a policy regulated by the government (or social planner):

$$\mathrm{TY_{t+1} = TY_t * (1 + g_{TY})} \text{ in which } \mathrm{g_{TY}} \text{ is the annual growth rate of TY} \quad (32)$$

In another attempt, I plan to propose two different methods (the second method is described in Appendix I) to include environmental erosion in the firms' cost-benefit analysis. To do that, I added an element of cost—which can be thought of as a carbon-tax factor—to the firms' energy profit maximization process, to internalize the cost of degrading the environment. Here, I am going to use Equation 6 [$\mathrm{ED_t} = 1 - (\mathrm{FE_t}/\varphi)^{\vartheta}$] which states that the environment degrades as more fossil fuel is being used. Thus, the profit function 27 would be:

$$\pi_t = \mathrm{P_{FEt}FE_t + P_{CEt}CE_t - w_tTL_t - r_tTY_t - CEX_tFE_t - SC_t} \quad (33)$$

$$\text{where: } \mathrm{SC_t = P_{SCt} * (1 - ED_t) \rightarrow P_{SCt}} * (\mathrm{FE_t}/\varphi)^{\vartheta} \quad (34)$$

in which P_{SC} is the price of eroding the environment and set by the social planner. Now, we can set the social cost in a way that the economic growth (or the total welfare) in the market-based model would converge to the one in the social planner solution by making the firm's profit equal to zero. We might call that price the optimal taxation policy on carbon emission. The results are shown in Figures 5-A.

There are three issues within this profit-tax framework, which need to be clarified. The first issue is the profit's existence in this model. Since the cost of extraction (CEX) is derived exogenously in this model, it allows the cost of fossil fuel-based energy to be lower than the revenue. Hence, the profit element can be evolved in this framework. The second issue is the impact of taxation on firms' decision. The assumption, here, is that firms can earn positive profit only if they extract and sell fossil fuel energy. Therefore, taxing their profit does not change their decision to shift their production toward clean energy, since producing clean energy is not profitable. The last issue involves a characteristic of the tax itself. The proposed tax is not exactly Pigouvian tax since it is not directly imposed on using fossil fuel energy, but on the profit which firms' earn from selling that energy. The idea, here, is not to limit or impact the firms' production decision by taxing the provision of fossil fuel energy but to channel the extra resources generating from that provision to boost up clean energy utilization.

Figure 5-B indicates that imposing a carbon tax element on fossil fuel production can bring back the market-based approach to the social planner solution. Figure 5-C shows that imposing the environmental costs of utilizing fossil fuel energy can limit the production in a similar way to the social planner approach. However, charging this tax does not increase the investment in the adaptation of clean energy advancement. Also, imposing the tax slows the utilization of fossil

fuel energy but not in line with the social planner's solution. Figure 5-A shows the optimum tax ratio while fossil fuel resources are being used to produce energy.

Figure 5-A shows the fossil fuel utilization—per peta watt hour—and the dollar tax rate per kilowatt hour of energy production using fossil fuel resources (which is around one cent per kilowatt hour). As has been shown before, the results in both scenarios (endogenous vs. exogenous population growth) do not vary having both sources of energy, but they differ when running out of non-renewable energy. In order to have the optimal taxation policy on fossil fuel utilization, we need to impose a U-shape taxation system which begins with the rate decreasing as firms use fossil fuels more intensively, and then increases when firms earn more profit.

Given the results in Figure 5-C, by regulating the market—imposing the investment rule in clean energy production—we can limit production but this regulation slightly increases the utility of individuals in a way that converges the results to the social planner approach. However—as a tradeoff—it causes a slower future capital accumulation. The results for the first policy implication show that such a policy would be ineffective.

Welfare analysis

Here, I intend to compare the effects of different model specifications (such as social planner vs. market-based approach) on the total welfare of the society, which can be seen as the utilitarian welfare function where all individuals have the same weight for the social planner over the horizon time discounted to the present value. Following Floden (2001), I am going to introduce the utilitarian welfare gain of model specification change as below:

$$W = \sum_{t=0}^{T} \beta^{t} U(c(t)) \tag{35}$$

Consider that the premium WG (compensating variation) can be thought of as the percent of consumption of individuals in economy B in each period, who need to be compensated in order to give up living in condition A, and move to economy B, which can be interpreted as the below equality:

$$\sum_{t=0}^{T} \beta^t U_A(c(t)) = \sum_{t=0}^{T} \beta^t U_B((1 + WG)c(t)) \quad (36)$$

Substituting the utility function, we are going to have:

$$\sum_{t=0}^{T} \beta^t \frac{{c_{At}}^{1-\sigma}}{1-\sigma} = \sum_{t=0}^{T} \beta^t \frac{(c_{Bt} * (1+WG))^{1-\sigma}}{1-\sigma} \quad (37)$$

Rearrange it for WG, and substitute back the welfare function, we get:

$$WG = \left(\frac{W_A}{W_B}\right)^{1/1-\sigma} - 1 \quad (38)$$

Using Equation 38—while W_A is the welfare in the social planner solution, and W_B is the welfare in the market-based approach—there is a loss in the welfare of the society of 0.033 if we try to move away from the centralized to the decentralized model, if population grows endogenously. It means in order to maintain the same level of consumption in a social planner, we need to compensate households for about three percent of their consumption in a decentralized model. This compensation amount, for the exogenous case, seems to be around the same amount of compensation between two different frameworks (3.3 percent versus 2.8 percent). However, this difference is about fifteen percent, considering an endogenous population growth instead of exogenous[20]. The results aligns with the previous findings in which

[20] The magnitude of this difference, considering the current US GDP, is around ninety billions of dollars per year.

social planner is the first best and market-based is the second, if firms do not fully internalize the negative externalities.

Undertaking the same process for the market-based model using different policies, we get the following results. Setting the time path for 180 years, there would be a negligible loss for no policy vs. policy-1. By applying the first policy, which was setting a rule in which the firms need to increase the financing of the clean energy production by five percent annually[21], there would be no gain and a small loss. By applying the second policy—which is the carbon-tax method—the gain would be more than two percent of consumption. Taxing the fossil fuel energy slightly influences the welfare. At the same time, it affects the future welfare while the production process is utilizing one hundred percent clean energy as a resource. Therefore, by imposing a tax on fossil fuel consumption, we can improve the total utility of the households in the long-run. The summary of compensating variations across different models is reported in Table 3.

Including endogeneity of population growth in any similar model shapes the future growth path and is twofold. First, we are overestimating the future growth path with any scale since we have not considered the feedback loop from the system to population itself (three percent difference on average in this framework). Second, in any decentralized economy, firms tend to utilize more resources to produce more. They ignore the negative externalities that arise from a production process. Because of this, there should be policy (preferably a carbon-tax tool) to improve the society's welfare. In this setup, seven percent of the consumption per year is a considerable amount—even as a higher bound—not to avoid the negative externalities existence that follows from fossil fuel energy use.

[21] I can increase that percentage, but it makes the model unstable after a few periods.

Conclusion

I proposed a dynamic growth model that allows for the interaction between an economy and an environment, utilizing both a social planner framework and decentralized method. Having no fossil fuel left, treating population endogenously leads to slightly lower growth in the economy relative to the exogenous population growth during the hundred percent renewable energy utilization. This result is rational in a sense that when population grows exogenously, any changes in the income level of households do not affect the growth rate in a population, which is a primary factor of production, itself. However, when we tie the population to the income level and other factors of the model, using a feedback loop, then any fluctuation in those factors directly impacts the population growth (and economic growth as a result). Switching from fossil fuel energy would not cause a drop in economic growth, since it would neutralized the positive impulse from removing the damage function that arises from fossil fuel utilization. Therefore, there would be a smooth transition from using both sources of energy to just renewable energy.

In the market-based approach, firms tend to utilize fossil fuel energy in a shorter period and invest more in clean energy, as opposed to the social planner method. Implementing a carbon-tax element on firms who produce energy speeds up adaptation of clean energy, and increases households' satisfaction due to the long-run higher rate of consumption, and recovers the partial loss that has been imposed by moving away from the first best scenario.

The long-run economic growth per capita converges to two percent in the current setup in which there is an exogenous technology with the growth rate of one point five percent. This result is opposite to the previous ones since growth in an economy is proportionate to growth in exogenous elements. Based on current findings, it is essential to include the endogeneity of the population in an economy since it prohibits any overestimation in growth prediction. The developed framework also allows for distinguishing the gap between a social planner and a market-based approach, and positives and negatives of each method regarding the projection of the growth path.

The future focus should be on expanding an idea of entering energy consumption heterogeneity into the current setup based on the availability of resources and different marginal costs of producing energy. On the other hand, households might not have a unique preference toward energy exploitation that can affect their energy consumption. Considering these sources of heterogeneity, a follow-up paper might lead to a different conclusion than I have investigated so far, which can lead to different policy recommendations than those I have already suggested.

II. Having skin in the energy game: The Impact of Social Norms on Energy Regime Changes

Introduction

Over the past three decades, concern about energy conservation has increased, mainly for environmental reasons such as urban air pollution and the threat of climate change. Energy forms are not all alike in their environmental impacts. Burning coal contributes more to urban air pollution than burning natural gas (Stern, 1992). Therefore, reforming energy resources is vital concerning environmental complication such as air and water pollutions. Since moving away from nonrenewable cheap energy is costly, there should be a strong motivation to change individuals' preferences to accept and pay the associated costs of energy adaptation. Social norms are one of the interventions that are commonly used in energy context to influence support for changes in environmentally friendly behavior (Steg, 2008; Allcott, 2011).

Social norms play an essential role in shaping how people interpret and compare behavior (Aarts & Dijksterhuis, 2003; Cialdini, 2003). Social norms are the rules or group-based standards regarding appropriate behaviors and attitudes (Schultz et al. 2007). The validity of social norms has been used in both economics and psychology studies. The effectiveness of descriptive social norms has been observed in pro-environmental behaviors, including energy and water conservation (Brager & Dear, 1998; and Jessoe & Rapson, 2014). Ferraro and Price (2013) use the average water usage of each neighborhood (as a social comparison) to induce households—of the same neighborhood—to decrease their consumption. One of the most important methods that has impacted individuals is through collective action, such as support for public policies and social movements to reduce greenhouse gasses through making financial contributions to social movements, voting, and signing petitions (Clayton et al. 2015). In their analysis, Minton and Rose (1997) indicate the effects of injunctive norms on the individuals' behaviors such as signing a petition to support an environmental cause, willingness to pay more taxes or money for electricity to support greater government control of pollution.

Any legislative approach to carbon emission will not fully recover the global warming crisis. However, Avi-Yonah and Uhlmann (2009) argue that a carbon tax can be a proper response to climate change through the necessary reductions in carbon emissions. Metcalf and Weisbach (2008) believe that a well-designed carbon tax might capture around eighty percent of the US emissions. However, a carbon tax is likely to be highly regressive which would put the burden on the bottom income decile compared to the top decile. Recent Canadian experience in British Columbia with carbon taxation approved the effectiveness of such policy in the reduction of the carbon emission (Harrison, 2012). Minton and Rose (1997) show that people intend to pay more taxes to support environmentally friendly policies. On the other hand, Alcott (2011) argues that there are several issues in regards to carbon taxation and clean energy subsidy. He believes that it has not been politically feasible to implement Pigouvian carbon tax. And while subsidies are in theory harmless, since they are transfers, they consume noticeable public funds in practice.

In the current exploratory study, I examine the impact of social norms on supporting for environmental policy in the energy reform context using survey analysis. More specifically, I provide various types of information for the respondents about the renewable and nonrenewable energy consumption rates. This information is going to be the percentage of renewable energy use, at the national level, in the US compared to the European countries and China. The survey for the control group asks whether the respondents are willing to sign a petition—adapting clean energy resources and moving away from fossil fuel energy—without providing the national comparison energy information. Then I ask the individuals the same question but with an additional information; this time the data comparing energy consumption in the US, EU countries and China are provided for them as a descriptive norm. After that, I verify if supplying different energy information sets affects their behavior supporting the petition. In the end, I ask the respondents who support the petition what type of taxation they prefer to subsidize clean energy: a carbon tax on energy producers or an increase in sales tax.

This research diverges from previous literature in two ways: first, the outcome of this study is driven based on the voluntary individual support for collective regulation rather than voluntary individual behavior changes; and the second, descriptive norm is framed at a group level rather than an individual level which has not been explored previously. While most of the research in the literature look for any changes at the household level and individuals' behavior, investigating the impact of descriptive social norms on collective actions using petition signing has been in a few studies such as Margetts et al. (2009) and Liu et al. (2016) in energy conservation context. Those studies emphasize using the same type of energy more efficiently, not switching to another energy. Another contribution of this study is that in the design petition, the households are asked to subsidize the renewable energy production either by paying higher sale tax rates by themselves or imposing a carbon tax on the energy producers. The intuition behind offering two tax policies is to verify whether the individuals are willing to bear the cost of subsidy directly by themselves or indirectly through the future energy prices.

The results show that providing the information about energy consumption of different countries has an impact on individuals' decisions. However, these effects are not always that we expect them to be. When the participants were informed about the energy utilization in China compared to the US—where China utilizes more fossil fuel energy than the US—they are more likely to sign the petition on the energy reform to move away from fossil fuel and invest more in clean energy. On the other hand, they are less likely to engage when they were notified about the European energy usage where those countries generates a higher percentage of clean energy compared to the US.

This paper is designed as follows: in the next section, the experimental design will be discussed, followed by the data description; in Section IV, the results of the study will be presented and discussed; in Section V, a power analysis for the future experimental design based on the results of this pilot study will be provided; in the end, a short conclusion will be examined; the survey itself would be displayed in Appendix II.

Experimental Method

I designed a petition (as a survey study), calling for energy reform, moving away from fossil-based energy to renewables—such as the wind, hydro, solar, nuclear and thermal energy. This would be funded by either an increase in sales tax by one percent to subsidize fossil-based energy producers to adopt other technology or charging fossil-based energy producers with the carbon tax (ten percent), and then subsidizing the producers who want to generate other energy sources.

The experimental method includes four petitions (one control group and three treatment groups). I have designed four survey links for four groups. Since the approved target population is twelve thousand faculty, staff, and students at Georgia State University, I randomly assigned three thousand to each group—prior sending out the surveys—in such a way that six thousand would be randomly selected from the faculty and staff pool, and six thousands from the students' pool. In the survey, after asking some basic information such as gender, income level, native or non-native to the US, and occupation, I provided the information about the effect of the carbon emission on the environment and human lives, including the carbon reduction by switching energy-based fuels.

The survey contains the energy usage—based on types—in the US at the national level. More than eighty percent of the US energy consumption is supplied by fossil-based energy, which produces more than 15 billion metric tons of carbon dioxide. The forests required to sequester the produced carbon every year in the US is more than 15 times of the existing forests in the US. Carbon emissions from coal are about 25 times more than solar PV to produce the same amount to generate electricity; and more than double about natural gas; and still around one-fifth of the total energy produces by coal because it is marginally cheaper and available, excluding the environmental damages it causes.

The US uses more fossil fuel than European countries, but less than China. Therefore, by providing the energy information about the countries who are utilizing more clean energy compared to the US, I hoped to nudge households to support for clean energy adaptation. Thus, in the first treatment, I added the comparison between European countries and the United States as a descriptive norm in which the US uses about 82 percent of her energy from fossil fuel resources, while this number is around 45 percent for European countries. The second norm is the comparison between the US and China, while China allocates 89 percent fossil fuel-based resources to cover her energy needs. Since China uses more fossil-based energy, it might be useful to verify the possible downturn effect of the social norm; in this case, people might think there is another country which is worse when concerning the environment. Participants would ask: “why should we care?” And the third is the comparison between the US, European countries, and China, all together, to verify the impact of the full exposure of the information. At the end of the petition, I asked participants if they are willing to sign the petition or not; if they agreed to sign, then I would follow with another question, asking whether they prefer sales tax increment or carbon tax reform on fossil-based energy producers to cover the costs. While the first treatment would directly affect the household’s costs, the latter increases individual’s living costs indirectly.

The purpose of this design is to test two hypotheses. The first hypothesis is whether providing additional information on country energy consumption—as a descriptive norm—can influence the households’ decision to support a petition in favor of clean energy. The second hypothesis is having the households’ support for subsidizing the clean energy, how should legislators proceed to provide the required resources for such subsidy—by imposing a carbon tax on energy producers which indirectly impact the consumers’ consumption prices, or increasing a sales tax which directly affects the prices. I speculate that the respondents would choose the carbon tax rather than the sales tax since they comprehend the immediate price effect. I think it would be crucial if the subjects believe that it is not a hypothetical survey and have actual impacts. Therefore, I included a paragraph in the petition that states that I plan to submit the outcome of this petition to Governor Deal. Since there is a high-cost associated with the petition, I thought that less likely people would sign it. This assumption gives me a powerful tool (since subjects realized that engaging this activity comes with the costs) to identify the effectiveness of the social behavior. The survey is shown in Appendix II.

Data

Table 7 shows the summary statistics of the collected data. All the variables in the table are categorical but income and age. Around 730 subjects started the survey; however, only 91% of them completed the study and responded to the central question (Will you sign the petition in either case?), leaving a total of 665 respondents which might not be sufficient for the analysis.

We can see that only thirty percent of the participants are students, which shows that the majority of the subjects might participate in the household decision making process since the average income of the respondents (around fifty three thousands of dollars) is close to the US average income and the median age (40) is close to the US median age (38). However, half of the participants hold a degree higher than a Bachelor's degree which is not the case for the US population on average. At least sixty percent of the subjects were married once; and the same percentage of the participants are female.

In general, slightly more than two-thirds of the respondents agreed to sign the petition in favor of the study. Less than one-third of them chose to bear the associated costs of investing in clean energy by themselves paying the extra sales tax to cover the expenses. There are a balanced number of respondents between all the groups but the third. The third group—in which the energy data between the US and China has been compared—had about one-third more participants than the average of the other pools together. Evidently, there are no meaningful differences between the summary statistics of the total respondent and the ones who selected into petition signing.

Results and discussion

Table 7 shows the core results of the research. Only six percent of the subjects who received the recruiting email responded to the survey (728 out of 12,000). And from this pool, ninety-one percent of them have finished the survey (665 out of 728). The number of the respondents who started the survey, and then completed it, are displayed in Table 7 in total and each group. Treatment 1 refers to the group who were informed about the energy consumption comparison between the US and European countries. Treatment 2 refers to the group who were informed about the energy consumption comparison between the US and China. And Treatment 3 refers to the group who were informed about the energy consumption comparison between the US, China, and European countries.

The results of the two tax proposal are documented in Table 7. We can see more than seventy-two percent of the individuals supported for the carbon tax, not the sales tax. It shows that the individuals are more likely to sign up for an environmental policy if it would not put any direct burden on them. In a separate attempt, I tried to verify the possible correlation between the respondents' characteristics and their decisions to sign the petition having the randomized dataset, while the main treatment analysis is also included. Table 8 shows the results of the Probit regression, where the dependent binary variable is either sign the petition or not. I dropped the individuals' income in the third column for two reasons: the first reason is the multicollinearity between the income and the respondents' education; the second is to not losing about sixteen percent of the data since just five hundred and fifty of the subjects have reported their income. I included the number of kids as a proxy for the cost of living and possible control for the income and any other backdoor correlation.

When the subjects asked to sign the petition, only 62.6 percent agreed to do such. However, more of the respondents opposed the idea of signing the petition just after the comparison of the energy utilization between the US versus European countries[22] was shown to them. This means the subjects responded negatively to the presented norm (the energy comparison between the US and EU). This outcome contradicts the previous findings in which consumers were more likely to act in favor of energy conservation, in an environmentally friendly manner. It is worth mentioning that singing the petition would be costly for the respondents in the future, since subsidizing clean energy requires resources. The individuals were informed that there are two channels to cover the costs: increasing the consumers' sales tax (which impacts them directly) or imposing a carbon tax on fossil fuel energy producers (which might affect them indirectly because energy producers may raise the prices). While the mentioned conclusion would be too strong based on the under power analysis—which is shown in Table 8—among control group and the first treatment group (the US versus European countries), it is noteworthy that there are two fundamental differences between this finding and the previous ones.

First, the social norm used here is at the national level, not for the people within a specific country. Individuals had different understandings and views about other countries prior to doing the survey. These realizations might have caused participants to form a judgment call when they made a comparison between their country and others. And if the information they were about to see would not have aligned with their judgments, the results might not have lined up with what one would expected. Align with this claim, Edwards (1968) showed that people are failing to revise their prior beliefs to absorb new information according to the Bayes' theory. Similarly,

[22] Where EU countries use a higher percentage of their energy as the renewable resources compared to the US

Lord et al. (1979) confirmed that strong beliefs are more likely resistant to alter even in the face of a thorough discrediting of their evidential basis.

The second primary differences in this study compared to its priors is that switching from fossil fuel energy to clean energy is costly; whereas, by conserving the energy—which is the case for the previous studies—the consumers benefit financially. These two distinctions may be the reasons for such differences between the current and previous studies.

In another comparison, when the subjects were given the energy information about the US versus China, they reacted differently. It is interesting that China utilizes more fossil fuel energy compared to the US in percentage, and I expected that either it negatively impacted their decision or nothing would have happened at all. Surprisingly, the attendants responded positively to this norm, and more people agreed to sign up for the petition. It seems that the respondents have already formed such a robust perception about the US-China comparison that aligned them in favor of the survey. They wanted this gap between the US and China energy utilization to continuously grow. In my perspective, the most compelling verdict of this study is the result of the first norm (US-EU) and the second norm (US-China). In both scenarios, the subjects were partially informed[23]; in such a comparison, one can see the power of the misdirection of the information. By not fully exposing the facts about the energy consumption of all the available countries to the subjects, one may orient individuals' decision to the favorable direction.

Table 8 confirms that the only positive and statistically significant outcome is when the respondents were informed about the energy consumption comparison between the US and

[23] Based on the design of this study, where the comparison among the US, EU, and China are considered the full information scenario.

China. If the second norm (the US vs. China) is presented to a respondent, there is forty-two percent more chance that she signs the petition compared to the control group. The third treatment—which is the full information state—is also positive but not significant; there is twenty-two percent more chance that a respondent signs the petition relative to the control group. And as it has been discussed before, the subjects adversely reacted when they learned about the energy consumption in the US and European countries; the magnitude of such conclusion is still negative while it is not significant. In this case, there is twenty-one percent less chance that a respondent does not sign the petition compared to the control group.

The analysis for the characteristics of the subjects shows that as the subjects become more educated, they are more likely—but not statistically significant—to care about the consequences of the energy production on the environment such as air pollution. The same argument can be driven looking at the occupation variable. It is more intriguing to see that when the respondents are getting older, they become less responsible for the environment or are more self-interested. This argument can be rationalized if one thinks about the consequences of older individuals, who are more likely to be closer to the end of their life than younger individuals. As a result, they may not prioritize evaluating the feasible environmental consequences of the energy utilization such as climate change and air pollution, in a way that younger generations do. The analysis on the type of taxation does not reveal any information about the characteristics of the respondents to either tax policies, as it is shown in Table 9.

Future experimental design

Based on the results of the current pilot study, now we can take a further step to perform a relevant power analysis to compute the required sample size for such experiment with two treatment groups and a control group. Table 10 shows the power analysis of the different comparisons among the three survey groups (C shows the control group, and T1-2 are for the different treatment groups). Power analysis in an experiment can determine how large a sample size should be to give us a reliable statistical judgment, and how likely we can detect the impacts within that given sample. The total sample displays the number of the required respondents in both compared groups. The alpha (α) represents the Type I error, and the power shows the one minus Type II error (1-β) in this statistical test.

In this analysis, the percentage of the respondents in the control group who would sign the petition is considered 62 %; while the amount is 55% for the first treatment (energy comparison between the US versus EU countries), and 77% for the second treatment (energy comparison between the US and China). Table 10 displays that to detect a significant difference between the control group and the first treatment, we need a large sample size which is not easy to get in a survey study. However, we have a better chance to discover any differences in other pairwise comparisons. The below is the formula that the sample size in Table 10 is built on which is one-way ANOVA pairwise analysis:

$$n = (p_a(1 - p_a) + p_b(1 - p_b))(\frac{z_{1-\alpha/2\tau} + z_{1-\beta}}{p_a - p_b})^2$$

$$z = \frac{p_a - p_b}{\sqrt{\frac{p_a(1 - p_a)}{n} + \frac{p_b(1 - p_b)}{n}}}$$

in which:

n is the sample size; α is the type I error; β is the type two error (so 1-β is the power); and τ is the number of the comparisons to be made which is 3 in this calculation.

Conclusion

I designed a field experiment, using a survey analysis, to identify the possible impact of the social norms on the individuals' decisions to support a petition in an environmental-energy context. In the survey, the subjects were asked whether to sign the petition or not, to change the energy utilization pattern and invest more in clean energy production. I used the energy consumption information from the United States, China, and European countries to form three separate comparisons as the social norms. In the end, I proposed two different tax policies and asked the respondents which they are willing to support.

The results show that while initially, less than sixty-three percent of the respondents were willing to sign up for the energy reform, more of the subjects would agree to do so when the information about the US-China energy usage was provided. The outcome of this research revealed that we can use a social norm as an influential tool in an energy reform context to increase individuals' support in an environmentally friendly policy. Moving away from fossil fuel based-energy and utilizing more clean energy, not only may help to restore the environment by a reduction in negative externalities arise from fossil fuel energy use, but also it can slow down the climate change by a contraction in carbon emission. This effort can also be used in a policy context in which achieving a super majority is needed. The respondents are more likely to support the carbon tax on energy producers to subsidize clean energy rather than an increase in the sales tax.

This research was performed at the university level—where respondents achieved a higher education compared to the average individuals in the US. A possible extension of this work could be a field experiment executed outside a university campus, where subjects' educational attainment would not be upwardly biased, and therefore, the results would be a better prediction of the society's aggregate understandings and willingness to participate in environmentally friendly reforms. Another challenge that should be taken into account in a similar future study is that a survey must design in such a way that can isolate any respondents' prior beliefs about the compared countries versus US, to unbiasedly determine any treatment effects that arise from providing new information on energy concepts. Including a question referring to the political party affiliation may help in that regard.

III. Energy Fallout: Air Pollution Effects on Environmental and Social Externalities

Introduction

Every year millions of people die because of the problems regarding air pollution across the globe[24]. There is also strong causal evidence connecting climatic events to human conflict over all the main regions of the world (Hsiang et al. 2013). In addition, air pollution has long-term effects on physical and mental health, which may encourage unprecedented illegal behaviors. Identifying the causes of criminal activity and mortality—which I call social damages in this research—are vital in compelling legislators to control and shift their effects by taking actions that can adequately address these concerns—specifically, in this study, air pollution for affected regions. On the other hand, air pollution is a result of human activities and is mostly generated utilizing fossil fuel-based energy.

Hanlon (2015) shows that industrial pollution had a substantial effect on the mortality rates during the nineteenth century. Anderson (2016) also finds the similar impact on the elderly in recent years. Heutel and Ruhm (2016) disclose a positive relationship between mortality rates and pollutants such as carbon monoxide, ozone, and particulate matter. The impacts of air pollution on health outcomes have been studied thoroughly (Folinsbee, 1993; Kunzli et al. 2000; Pope et al. 2002). Kampa and Castanas (2008) claim that air pollution has severe impacts on human health. Air pollution then influences different organs and systems causing conditions such as bronchitis in adults and lung cancer, asthmatic attacks, and heart-related issues.

[24] The Global Burden of Disease from Air Pollution; AAAS 2016 Annual Meeting, Washington, DC.

Air pollution may also affect criminal activities, directly or indirectly. Cohn (1990) discusses the theoretical background and verifies the influence of different weather conditions on various types of criminal behavior. Masters et al. (1998) explore the hypothesis that absorption of neurotoxic metals may be partly responsible for the extremely high and widely varying crime rates in the United States. In the study most closely related to this research, Herrnstadt and Muehlegger (2015) apply data on two million illegal activities reported to the Chicago police department in a twelve-year interval. Consistent with evidence from psychology on the correlation between pollution and aggression, the impact is unique to violent crimes; they could not find any effect of contamination on property crime.

There is a possible causation between household income levels and a higher likelihood of illegal activity (Viscusi, 1986; Freeman, 1987; Grogger, 1998; Weinberg, et al., 2002). There is also a rich body of literature examining the association between population density and the prevalence of crime (Sacerdote & Glaeser, 1999; McDonald & McMillen 2010). Glaeser (1996) and Sun, et al. (2004) claim that property rates can influence crime rates. Air pollution can affect individuals' income (Selden & Song, 1994; Carson et al. 1997), housing values (Ridker & Henning, 1967; Anderson & Crocker, 1971), and city size (Grimm et al. 2008). Therefore, it might arouse criminal activity indirectly via these factors. Thus, I can build a bridge from criminal activity via air pollution that arises from energy consumption.

The purpose of this study is to estimate the impact of energy consumption—making a distinction between fossil fuel energy and clean energy[25]—on reported crimes and mortality through the air pollution channel, using the mechanism approach. Given the existing correlation

[25] In this study, clean energy refers to the solar, hydro, wind, nuclear and biofuel energies.

between air pollution and criminal activity, and previous studies limited to particular neighborhoods, the challenge is to verify whether the results are generalizable and confirm causation. The use of cheap energy, such as coal or gas, leads to higher air pollution than clean energy, such as solar and wind; however, implementing cheaper energy decreases the production costs, and therefore, more production, which results in higher income. Given the high correlation between income and criminal activity, higher income leads to a lower rate of illegal activities, and at the same time higher living standards lead to lower mortality rates, while using clean energy has an adverse effect through the production/income channel. Accordingly, there is a trade-off between using cheap fossil fuel energy and more expensive and clean energy, in which both types of energy may decrease the social damages: the first one through higher production rates, and the second one through lower air pollution. Ultimately, the answer of which method may reduce both criminal activity and mortality is an empirical question which is pursued in the current research.

I use state-level data from all available states across the US, whereas in previous investigations, authors usually have used data specific to one or few regions (Herrnstadt & Muehlegger, 2015; Anderson, 2016; Liu, 2017). Thus, the idea is that the external validity of their results might not be generalizable across the US—given the internal validity is reliable. While data used in the previous findings is daily and identifies the short-term effects pollution has on crime, I benefit from the yearly data to determine the long-term effect of air pollution on reported crime. Given the possible existence of the omitted variables and endogeneity at the state level, I utilize Oster's (2017) method to control for the selection of an unobservable variable to account for unforeseen problems. And in other attempt, I utilize political affiliations of the governors of each state as an instrument for an additional robustness check. It must take into account that the political affiliation might not be a valid instrument since the exclusion restriction is hard to believe.

I set up an empirical model—using mechanism approach—to verify the impact of air pollution on crime and mortality rates, given the current trade-offs of energy adoption and production/income level. Air pollution has been shown to affect a variety of outcomes—including crime and mortality—but air pollution partially comes from energy use, and that energy use affects crime and mortality through other mechanisms such as income. Thus, a more comprehensive empirical analysis would be to examine the causal effect of energy use on crime and mortality, and estimate the countervailing mechanism effects that come via pollution and via income. Given the results, the contribution of this work is that air pollution escalates both violent crimes and mortality rates caused by fossil fuel energy consumption. At the same time, as the use of fossil fuel-based energy rises, income tends to increase while both mortality rates and criminal activities decrease. The empirical results can confirm that as the air becomes more polluted, the likelihood of a rise in crime in that neighborhood increases as a result, as does mortality induced by fossil fuel energy. Accordingly, there is a trade-off between using cheaper, contaminated energy (which leads to more production), and utilizing cleaner, expensive energy and polluting less (which leads to less production).

This paper is formatted as follows: in the next section, I adopt an empirical model, utilizing the mechanism approach to distinguish the correlations among the drivers of violent illicit activity and mortality, followed by a description of the extracted data in the successive section; then, I analyze the possible correlations among the different variables, discuss the results and possible rival explanations for the proposed analysis' limitations, and take advantage of an instrumental variable (IV) approach; and in the end, I perform a comprehensive analysis to authenticate the validity of the outcomes. To do this, I take advantage of the Oster (2017) method for selection of observable variables on unobserved, as well as a sensitivity analysis, followed by a conclusion.

Empirical model

Figure 10 shows declining trends for the air pollution as a negative externality, total reported crimes, and mortality rate over the studied period, while the total use of fossil fuel-based energy relative to the total energy consumption has had a negative direction as well[26]. Given the impact of economic activities on air pollution, and the possible effect of the latter on crime rates and mortality through channels such as health outcomes or educational quality, I build my model in which energy utilization is the independent variable, and the crime rates and mortality rates are the dependent variables. Production (total income as a proxy) has a negative impact on illicit activities (Hansen & Machin, 2002), while at the same time might have a positive effect on the illegal endeavors via air pollution. Therefore, the critical question is whether the overall impact of the energy used in production has an effect on crime rates and mortality considering both direct and indirect effects (via air pollution) in the US.

Figure 11 displays a summarized identification strategy as a flowchart. It is shown that energy use affects both air pollution and income at the same time, while these two influence the latent variables (criminal activities and mortality rates). Within this structure, there are other control variables that interact with the key variables of the study (independent variable, dependent variables, and the mechanisms) at the same time. It is also depicted that there is a reverse

[26] Data description is explained in the following section

causality between income and energy use which can bias the results. Another challenge I am facing is that crime might have a reverse effect on production (the same as air pollution). And also, higher income level can impact environmental policy. Therefore, finding a key factor, which has a high correlation with production (and air pollution), but not criminal activity, is vital.

To address such an issue, I employ energy consumption, based on state-level data retrievable from the US Energy Information Administration (EIA). Air pollution is a direct effect of energy consumption; therefore energy can be a powerful explanatory variable for air pollution. However, energy use is a primary factor of production, so it is connected to criminal activity indirectly. Therefore, air pollution is not the only channel that connects energy consumption to crime and mortality, but rather production/income also makes the same connection. To verify this hypothesis, I apply the mechanism effect approach. I implement Imai et al. (2010) for the mechanism approach. The key to understanding the mechanism effect is the following counterfactual inquiry: how would the outcome differ if one were to alter the mediator from the control condition value to the treatment condition value while maintaining the treatment status at the same level? However, identifying the treatments of mechanism via control conditions is hard to detect since this study is built on a multi-valued treatment and multi-valued mechanism.

To measure the mechanism effect, I first verify the impact of energy consumption on the dependent variable: violent crime rates and mortality rates (Equation 1). Then, I measure the incidence of energy (fossil fuel and clean, separately) on the proposed mechanisms: air pollution and production (Equation 2). Last, I estimate the original model (including all the proposed variables) (Equation 3). Therefore, these equations are estimated separately, at different steps. It is important to note that the variation in the current analysis comes from the states' government. Each state, based on the availability of natural resources and geographical condition, chooses the type of the energy that optimizes the level of production and prosperity.

$$Dependent\ variable_{it} = \alpha_{1i} + \delta_{1t} + \beta_1 Energy_{it} + \varphi_{1j} X_{ijt} + \varepsilon_{1it} \quad (1)$$

$$Mechanism_{it} = \alpha_{2i} + \delta_{2t} + \beta_2 Energy_{it} + \varphi_{2j} X_{ijt} + \varepsilon_{2it} \quad (2)$$

$$Dependent\ variable_{it} = \alpha_{3i} + \delta_{3t} + \beta_3 Energy_{it} + \gamma Mechanism_{it} + \varphi_{3j} X_{ijt} + \varepsilon_{3it} \quad (3)$$

In the equations above, *Dependent variable* can be either crime rates or mortality rates. *Mechanism* can also be air pollution or production. For *Energy* as an independent variable, I use two different elements: fossil fuel-based energy, and coal-based energy[27]. Therefore, I evaluate the above system of equations eight different times for each estimation (each dependent variable with each mechanism separately for each energy type fuel). α_is and δ_ts are state-fixed and year-fixed effects respectively. X_{ijt}s are the covariates that are controlled for, such as housing prices, number of police officers, unemployment, and year trend. Since the regional data might be correlated with time, I enter the time trend to control for such correlation. It must be noted that in order to make this approach work, one needs to isolate the mechanism from the interaction between the independent variable and dependent variable. This is a strong assumption in this analysis, where the major elements of the study have a strong correlation with each other and the controls—at the same time—which can jeopardize the true impacts of the treatments.

[27] The reason to make a distinction between fossil fuel-based energy and coal-based energy is to verify whether excluding petrol and natural gas from fossil fuel-based energy can possibly worsen the impacts solely because of coal.

After estimating each linear equation via least squares, the product of coefficients method uses $\hat{\beta}_2\hat{\gamma}$ as an estimated mechanism effect. Similarly, the difference of coefficients method yields an identical estimate by computing $\hat{\beta}_1 - \hat{\beta}_3$ in this linear case. Because $\hat{\beta}_1 = \hat{\beta}_2\hat{\gamma} + \hat{\beta}_3$ and $\beta_1 = \beta_2\gamma + \beta_3$ always hold, Equation 1 is redundant, given Equations 2 and 3. Thus, I compute $\hat{\beta}_2\hat{\gamma}$ as a mechanism effect for two energy regimes (fossil fuel-based energy and coal-based energy) to verify the impacts on both violent crime rates and mortality rates. There are two different values for the mechanism effect ($\hat{\beta}_2\hat{\gamma}$): one for the air pollution, and the other for the income. If this value would be positive and significant for the air pollution, it means that utilizing more fossil fuel energy leads to the higher rate of crimes (or mortality) channeling through the air pollution. The same explanation is valid for the income channel.

Given the possible impact of air pollution (resulting from different energy regime consumption) on mortality rate and crime rates through channels such as health issues and educational quality, it may be useful to find a key factor which has a high correlation with air pollution but not latent variables and use that instrument in an analysis. Specifically, pollution, mortality rate, and criminal activity are all likely to be correlated with seasonal trends, coincidental weather conditions and unobservable occurrences such as economic activity. Another serious threat to the proposed identification, as it has been stated before, is the existence of reverse causality between energy use and income, which I cannot address this concern properly within the structure of the proposed method.

To address such an issue, in another attempt, I utilize political party affiliation—if the governor is a Democrat, Independent, or Republican—as an instrument for energy consumption. The proposed approach is nested in the idea that the Democratic Party supports more environmentally friendly regulations; therefore, they might impose more restrictions that conserve the environment. Conversely, the Republican Party's approach relaxes those environmental laws and regulations suggested by the third entity. However, political affiliation is a weak IV since the excludability might be violated due to a correlation between political viewpoint, income, environmental policy, and living standards, and then, living standards, mortality rate, and criminal activity. Therefore, energy consumption is not the only channel by which the IV impacts the dependent variable. If one thinks the only (indirect) path from the IV to the dependent variable should pass through the energy channel, then, it does not satisfy the exclusion restriction.

To verify the current approach, I apply a two-stage OLS method, while using political affiliation as an IV for energy consumption to derive the average treatment effect. The analysis would be as follows, and will be estimated simultaneously:

$$Energy\ consumption_{it} = \delta_{4i} + \gamma_{4t} + \beta_1 Pol\ aff_{it} + \theta_j X_{ijt} + \epsilon_{1it} \quad (4)$$

$$Dpendent\ variable_{it} = \alpha_{5i} + \gamma_{5t} + \beta_2\ Energy\ \widehat{consumption}_{it} + \varphi_j X_{ijt} + \epsilon_{2it} \quad (5)$$

In Equation 4, the independent variable is *Energy consumption*. δ_i, α_i and γ_t are the state level and time fixed effect to absorb any potential structural differences across the cities. X_{ijt}s are the covariates that are going to be controlled by housing prices, air pollution, median income, rate of unemployment, year trend, and number of police officers (while violent crime is *Dependent variable*) or total crime (when mortality rate is *Dependent variable*). I also can use the annual change of the variables to mitigate the possible yearly effect and auto-correlation at the same time, or enter a year trend variable.

Data

I use state-level data for all US states including Washington DC (DC) from 2001 to 2015 to examine the connection between energy utilization and social damages[28], channeling through air pollution and income. I collect the data for energy consumption from the US Information Administration (EIA) at US Department of Energy[29]. Energy data is available for all the power plants—which extracted from power plant operations report—in each state, which generate electricity specifying the types of fuel they use. It contains monthly information about the heat and power plants across the US reported fuel type codes for boilers and cooling systems. I utilize the input fuel-based energy that any power plant uses to generate power, not the actual electricity that a plant generates as an output. This is because using fossil fuel directly may cause air pollution by emitting carbon or any other toxic particles. This data set uses state-level aggregate energy consumption, which is of its shortcomings since energy utilization of other sectors such as the motor vehicle is not included. Even though I may collect other sectors' data at the state level and add it to my current data, this addition creates an extra concern since vehicles are mobile across the borders.

The data for population, number of police officers, and reported crime rates are collected from the Federal Bureau of Investigation's online uniform crime statistics (UCR)[30]. The yearly information is publicly available for each region and state based on two main categories of crime such as violent crimes (murder, rape, robbery, aggravated assault) and property crimes (burglary, larceny-theft, motor vehicle theft, arson) and also sub-level categories that are mentioned.

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[28] Which in this study are mortality and violent crime
[29] https://www.eia.gov/electricity/data/eia923/
[30] https://ucr.fbi.gov/crime-in-the-u.s

Using the Centers for Disease Control and Prevention Data Center, I extract the data for the different mortality rates based on the causes of death[31]. The Compressed Mortality database, which is publicly available, contains population and mortality counts for all US states and counties. Rates and counts of death are accessible by underlying cause of death and year. Data are also available for the different race, gender, injury intent, and injury mechanism. One can request the yearly data from studied period. The underlying cause of death is specified such as circulatory conditions (refers to the problem with hearth and blood vessels) and respiratory diseases (such as asthma and lung cancer), external causes, and overall death counts.

Here, I use particle pollution[32] (PM10) as a proxy for air pollution which is a mixture of airborne liquid droplets and solid particles. Particle pollution varies by geographic location and season and is affected by various aspects of weather such as humidity, temperature, and wind. The major components of these particles are carbon, nitrate, and sulfate compounds, along with crystalline elements such as ash and soil. The chemical makeup of these particles varies across the US. Yearly observations for PM10 are retrieved from the US Environmental Protection Agency database[33].

I extract and pool the data of housing price index as a proxy for the housing prices from the Lincoln Institute of Land Policy[34]. Then, I merge the data of household median income from the US Bureau of Labor Statistics (BLS) to calculate the level of production by multiplying median income by the population[35]. I also use the unemployment rates in different states, which may

[31] https://wonder.cdc.gov/cmf-icd10.html
[32] Data for PM2.5, CO, NOX, SO_2 is also available in my dataset.
[33] https://aqs.epa.gov/aqsweb/airdata/download_files.html
[34] http://datatoolkits.lincolninst.edu/subcenters/land-values/land-prices-by-state.asp
[35] https://www.census.gov/topics/income-poverty/income/data/tables.html

play a significant role in the analysis based on its emphasized position and how it can incentivize jobless individuals to commit a crime.

The constructed dataset has 50 states' information plus DC. Table 1 shows the summary of the statistics, which are used in the analysis. DC has the minimum amount of clean energy use, which is zero (during the studied period). PM10 emission figures for 2014 and 2015 are not available for DC. Power plants in DC also do not use coal-based fuel over the studied years according to the applied database.

Data for energy consumption is available at the plant level in each state. To obtain the state-level data, I aggregate the data to find the sum of energy use at the state level. Doing so may cause an issue due to the aggregating data, specifically in panel data analysis. To address this concern, I use the weighted least-squared approach in which the number of the energy plants are used as the weights.

Results and Discussion

Following the proposed steps, and using the yearly data for all US states from 2001 to 2015 at the state level, pooling from the CDC, FBI, EPA, EIA, BLS, and LILP databases, I report the primary results in Table 12. It must be noted that data for violent crimes, production, number of police officers, energy consumption, and mortality rates have been normalized by state population per hundred thousand. Table 12 shows the impacts of different elements of this empirical model on the social damages (violent crimes and mortality). While air pollution and income are introduced in this study as mediators between energy utilization and social damages, there is still significant impacts from using different types of energy on the dependent variables despite controlling for these two mechanisms. It raises this valid concern: that there might be other direct or indirect impacts of energy use on violent crimes and mortality which are not considered in this analysis.

In this study, energy consumption (total energy consumption, fossil fuel-based energy, and coal-based energy) and air pollution elevation increase the likelihood of both violent crime rates and mortality rates, while income decreases such a chance on the latent variables. Increasing the total energy consumption by one million BTU per hundred thousand habitants escalates the violent crime rates by almost 0.2 percent. This amount increases the mortality rates by around 0.07 percent. While the increments of the violent crimes do not roughly vary across different energy regimes, switching the total energy to coal-based energy surges the negative impact on mortality rates by three folds (from 0.07 to 0.24).

Here, I am not only interested in the sign of the impact (positive or negative) but also the exact level of point estimates, since the existing trade-off between lower pollution and higher income makes the ultimate impact unclear. Tables 13 and 14 show the main results for mechanism analysis when the dependent variable is violent crime rates. In the first table, air pollution is the mediator between energy utilization and violent crime rates, while in the latter table income is the mediator. This is the point, we can compute the magnitude of the impacts of each mechanism separately[36]. The effects of air pollution that arise from fossil fuel-based energy and coal-based energy on violent crime rates are 1.37E-4 and 6.9E-4, respectively. It means that violent crime rates increase by almost 0.01 percent through air pollution in the affected regions

[36] $\beta_2\hat{\gamma}$, in which β_2 is the coefficient of the energy in regressing the mechanism as a dependent variable [Equation 2], and $\hat{\gamma}$ is the coefficient of the mechanism in the final regression [Equation 3]; combined, I have my mechanism impact

when one million BTU of fossil fuel-based energy is used. This amount hikes to 0.07 percent when fossil-based energy is replaced by solely coal-based energy. Similarly, we can compute the effects of income as the mediator on violent crime rates. The following values are obtained: -2.4E-5 when fossil fuel-based energy is used, and -1.039E-4 when coal-based energy is used. It implies that violent crime rates decrease by nearly 0.002 percent and 0.01 percent due to the one million BTU fossil fuel-based and coal-based energy utilization, respectively.

Tables 15 and 16 display the related results when the dependent variable is mortality rates. In Table 15, air pollution is the mediator between energy utilization and mortality rates, and in Table 16, income is the mediator. Accordingly, we can calculate the effects of each mechanism independently. The impacts of air pollution that emerge from fossil fuel-based energy and coal-based energy on mortality rates are 2.8E-5 and 1.39E-4, respectively. It indicates that mortality rates decrease by about 0.003 percent through air pollution in the contaminated areas when one million BTU of fossil fuel-based energy is utilized. This amount boosts to 0.01 percent when solely coal-based energy is substituted. Likewise, we can calculate the impacts of income as the mediator on mortality rates. The results are -7.7E-5 when fossil fuel-based energy is utilized and -5.35E-4 when coal-based energy is utilized. It signifies that mortality rates diminish due to the one million BTU fossil fuel-based and coal-based energy utilization by approximately 0.007 percent and 0.05 percent, respectively.

Diving more deeply into the results to calculate the mechanism impacts, we can see that the impacts of air pollution on violent crime rate—in both studied energy regimes—are greater than the effects of production (the mechanism effects for the air pollution are 1.37E-4 & 6.9E-4 vs. -2.4E-5 & -1.039E-4 for the production as a mechanism); therefore, the ultimate effect of energy utilization (fossil fuel-based energy and coal-based energy) on criminal activity—via air pollution and income channels—is positive (which is not favorable). The opposite effect is noticed in the mortality rate scenario. While utilizing fossil fuel energy causes more pollution in the region of analysis, it correlates with higher rates of death because of lower production and income levels (the mechanism effects for the air pollution are 2.8E-5 & 1.39E-4 vs. -7.7E-5 & -5.35E-4 for the production as a mechanism).

The results convey that utilizing more fossil fuel-based energy elevates air pollution but does not lead to increased criminal activity and mortality rates at the state level in a similar direction. Changing the energy sources from clean to fossil fuel-based—as a primary factor of production, thus, income—has a positive impact on household income; therefore, by increasing living standards, fossil fuel energy diminishes mortality rates but not crime rates. Thus, it is the case that switching from fossil fuel energy to clean energy exacerbates mortality rates but alleviates criminal activity[37].

The results—using the IV approach—are depicted in Table 17. In this analysis political affiliation is granted as the instrument for energy utilization[38]. Air pollution and income are the important elements that are being controlled in this evaluation; hence, I do not perform the mechanism approach. We can see that energy utilization does not have any significant impact on violent crimes and mortality rates (although the magnitude of the effect is negative). There is no effect from income on the latent variables as well. The results show that death rates increase

[37] Coal-based and clean-based comparison has been conducted in the appendix.
[38] If a governor of a state considers himself or herself as a democrat or republican.

significantly due to air pollution. While we can observe the similar effect on the violent crime rates, this influence is not statistically significant.

The IV shows that if we control for income and air pollution, the impact of the different energy utilization on the social damages drops to zero; however, it is not the case in the mechanism analysis. Since political affiliation is not a reliable IV (it can correlate with both air pollution and income level—because of the possible contrasting policy scenarios due to the differences in political viewpoints), we cannot exclusively have confidence in the derived interpretations from this outcome. The result from the first stage analysis shows that the political affiliation does not significantly correlate with the fossil fuel energy consumption. Therefore, I conduct various robustness checks to verify whether the results of the mechanism analysis are trustworthy.

Robustness check

Testing for the omitted variable

Since I do not use a valid instrument to control for possible endogeneity, here, I try to take advantage of the Oster (2017) proposition—that is built on Altonji et al. (2005) approach—which indicates the magnitude of the selection of the observable to estimate the impact of the unobservable in the model facing the endogeneity issue. The objective is to measure the primary model's sensitivity to the key control variables, based on the changes in R-square—which can explain the variation of the specified elements in the model on the dependent variable—and the shifts in the main coefficient[39]. Therefore, if the main coefficient does not vary relative to the changes in R-square while control variables are included in the model, then we can conclude that the coefficient is robust and presents the real effect. Table 18 shows the analysis for the violent crime rate variable that gives us some insight about the sensitivity of the coefficient of the independent variable to the control elements. We can see that including the control variables (such as the number of police officers, and unemployment rates, housing prices, and year trend), while increasing the R-square by one unit, decreases fossil fuel-based energy coefficients by more than one unit. This amount is less than one unit for coal-based energy. This more complete model suggests that fossil fuel energy may explain causation in violent crime rate through the proposed channel. In Table 19, we can observe the same analysis and results for mortality rate, which suggests that there is a causation between the explanatory variables (fossil fuel-based energy and coal-based energy) and the dependent variable (mortality) in the constructed model[40].

Placebo test

Previously, my discussion focused on the effect of energy changes on violent crime rates. Another approach to validate the results is performing the same analysis but changing only the dependent variable. To test that hypothesis, I switch the focus from violent crime rates to property crime rates, and verify the results. The idea here is that the air pollution can affect health outcomes, impact the nervous system, and can result in violent crime but not property offenses such as burglary. The same may be true for energy's effect on death rates. Since air pollution does not affect all variations in the type of death, I can take advantage of it and perform

[39] Here, I assume that the primary model is when energy use is independent and dependent variables are crime rates and mortality rates, and the rest of the variables are assumed to be controls. And the reason for doing so is to verify if energy use has any identifiable impact (using the merged dataset) on the latent variables in the first place.
[40] It shows that the impact of the unobservable on the coefficient of the independent variable is negligible.

the analysis changing the dependent variable from circulatory problems to external causes (which includes accidents, for example) and validate the conclusion.

Results are summarized in Tables 10 (for violent and property crime rates) and 11 (for circulatory conditions and external causes). Table 20 confirms that while air pollution via energy utilization increases violent crime rates, it does not affect property crime rates. This hypothesis is valid when the independent variable is coal-based energy but not fossil fuel-based energy. This test does not reveal any income impact on the latent variable. Table 21 supports the unfavorable effect of air pollution on mortality rate. While air pollution increases the circulatory conditions, it does diminish the external cause of death (which could potentially be a problem). On the other hand, income decreases the circulatory conditions but not significantly decreases the external causes. This outcome gives us a level of confidence in identifying a strong correlation, even causation, between energy consumption and mortality rate channeling through air pollution and income. In another attempt, I compare the results between the clean energy and coal-based energy in Appendix III.

Sensitivity analysis for the mechanism design

Imai et al. (2010) propose a falsification test for a causal mechanism analysis based on the correlation between the error for the mechanism model, ε_{2it}, and the error for the outcome model, ε_{3it}. They argue that this correlation between the two error terms serves as the sensitivity parameter. Such an association can arise if there are omitted variables that affect both mediator and outcome variables, since these omitted variables will be part of the two error terms. This proposed test differs from the test of omitted variable in the first section of robustness check since in this section I try to validate the mechanism approach and verify whether there is an omitted variable within this specific approach. However, in the previous test, no mechanism has been detected, and all the other elements—aside from the dependents and independent—are assumed to be controls. Another variation between these two tests is the way that we perform them and how to detect the omitted variable. In the current approach, we try to disclose any correlation among the error terms in both mechanism model and the full model. However, in Oster's approach, we are looking for the robustness of the main coefficient to the presence of the control variables.

As it is tested separately (in Table 22 for both mortality rates and violent crime rates while the independent variable is fossil fuel-based energy), no significant correlation between the error terms has been detected. The same analysis has been conducted when fossil fuel-based energy is replaced by coal-based energy, and identical results have been driven. Executing this test suggests that the likelihood of having an omitted variable in the proposed model using mechanism design is low.

Income effect

There is an ongoing discussion between the correlation of a country's income level and the willingness to apply environmental policies such as subsidizing clean energy. The idea is a nation needs to reach a certain level of wealth to start regulating the environment. While this debate focuses on developing and developed countries, it might play a role among different states as well, since a state like Mississippi earns around forty thousand dollars per capita, while New Jersey earns double this amount per year. Table 23 shows such analysis, which does not reveal any new information.

Conclusion

In closing the above discussion, I conclude that utilizing more non-renewable and cheap energy increases mortality rates—such as circulatory problems—and the possibility of having violent crimes—but not property crimes. Additionally, non-renewable energy imposes slightly less economical cost while having its environmental damages within the context of the study. The findings can point out the highly significant correlation and possible statistical causation between fossil fuel-based energy utilization and social damages—such as violent crime and mortality rate. Consuming fossil fuel energy increases both income level and air pollution; at the same time, air pollution boosts up social damages while income reduces them. The results show that income channel outweighs air pollution channel when the latent variable is mortality rates. Therefore, employing fossil fuel energy is in our favor. However, the adverse results are obtained when mortality rates are substituted by violent crime rates.

It must be taken into account that the US spends more than $28 billion dollars on the justice system (yearly, at the federal level), while at the same time more than 9,200,000 crimes occurred in the US. Having considered half of the budget as a fixed cost, the Justice Department spends around $1,500 per crime, using a rough calculation. Decreasing illegal activities by just one percent can reduce the cost by more than $140,000 per year. The rough calculated amount can give us an incentive to understand the social cost hidden in the crime, which has not been included in our economic analysis. An interpretation of such social damages is vital to incorporate if one wants to include those expenses to compute the more accurate production cost analysis. We need to add the percentage changes in mortality rate as well (by saving health costs), which can suggest an even higher amount of neglected social expenses in our cost analysis of choosing the type of energy to consume.

The primary aspiration of this research is to study the trade-off between utilizing cheaper, contaminated energy to produce more, and using cleaner, expensive energy to pollute less. Therefore, it is crucial that policy makers are convinced that the analysis is decisive. Accordingly, finding an accountable exogenous variation seems to be the vital clue in this application. Thus, a possible extension of the current work would be employing a relevant energy policy change in any state during the studied period to administer a causal analysis. States such as Massachusetts, Washington, and California have adopted different energy acts in previous years which can be suitable for the intended exploration.

Appendix to Chapter I

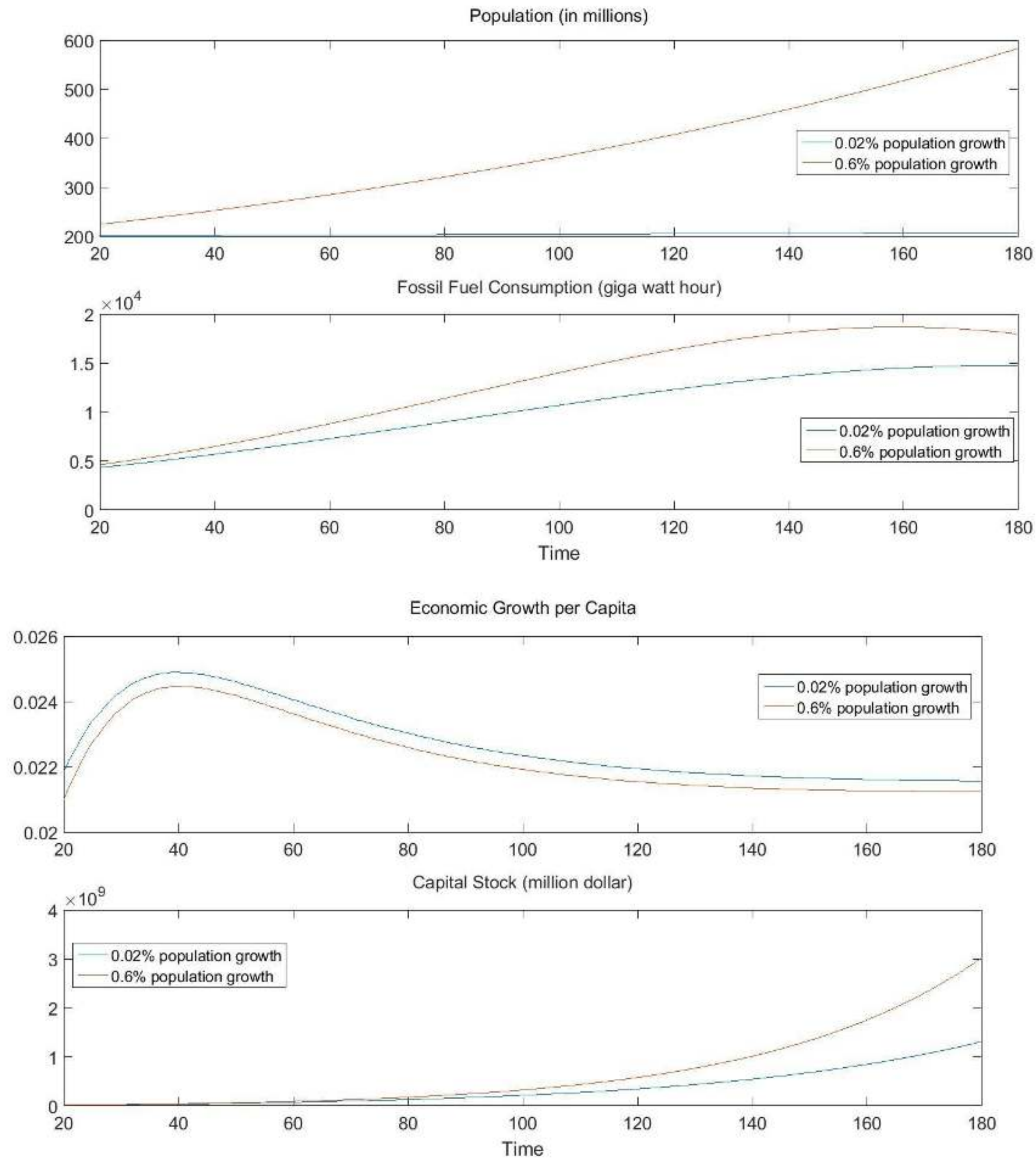


Figure 1: Different growth rate in population for the social planner solution.

Figure 1 shows population growth (the U.S. labor force), fossil fuel utilization, economic growth and capital accumulation, while a population grows by 0.02 % (blue lines) and 0.6% (red lines) per year. The population grows exogenously and the social planner solution has been applied for both cases.

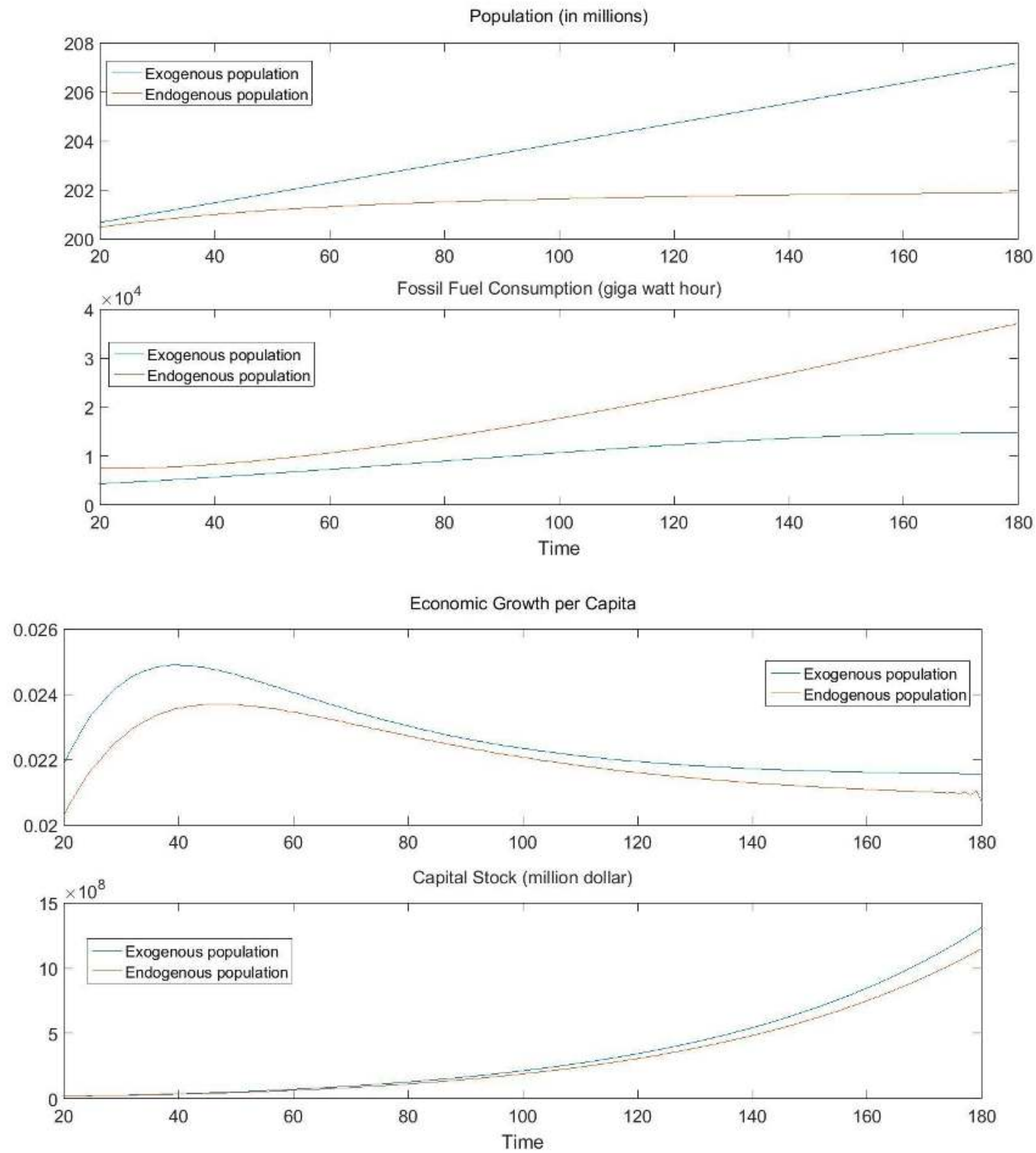


Figure 2: Exogenous population growth versus endogenous for the social planner solution.

Figure 2 shows population growth (the U.S. labor force), fossil fuel utilization, economic growth and capital accumulation, while a population grows endogenously (red lines), and when population growth is exogenous, and equals to 0.02% (blue lines). The social planner solution has been applied for both cases.

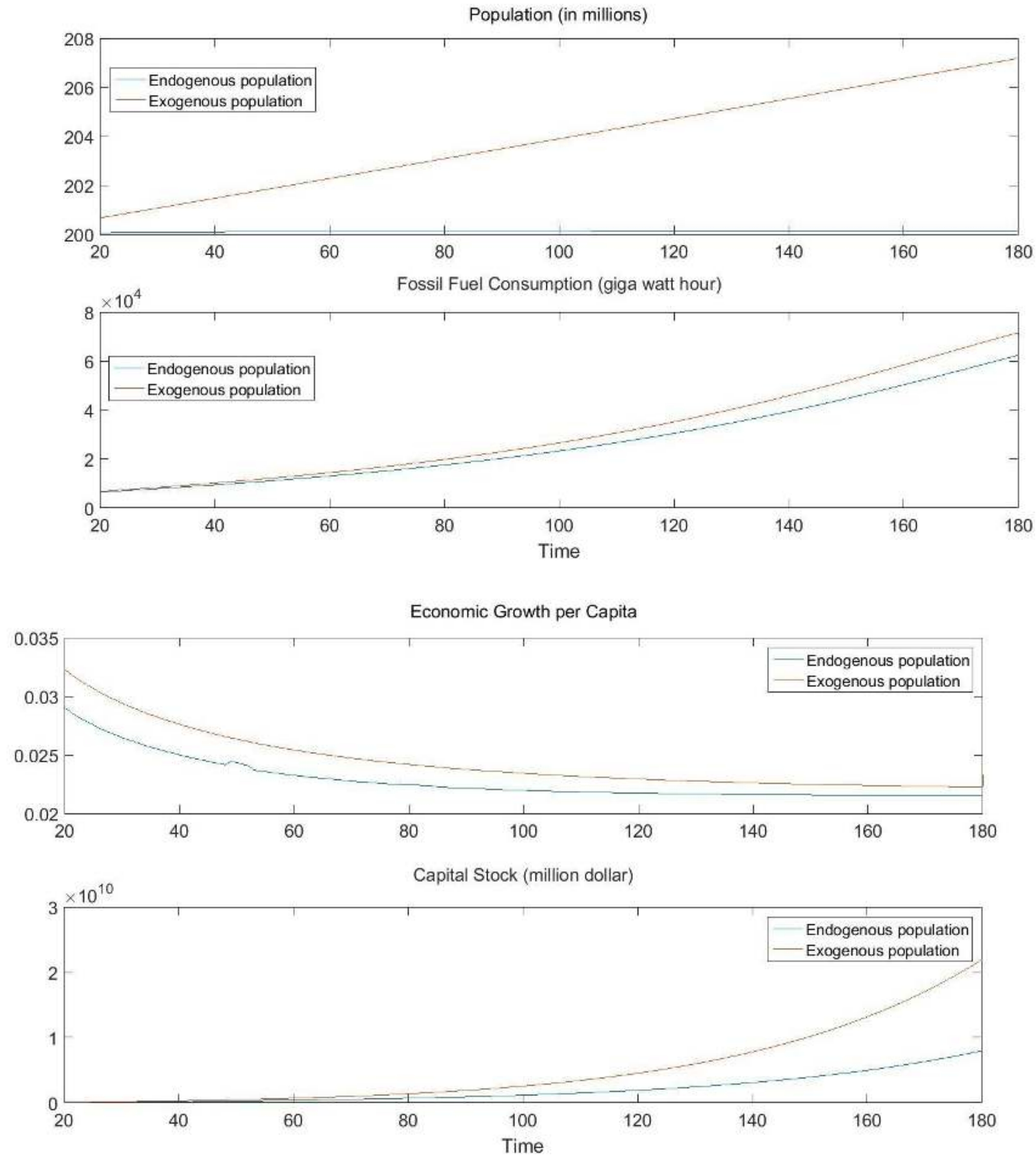


Figure 3: Exogenous population growth versus endogenous for the market-based approach.

Figure 3 shows population growth (the U.S. labor force), fossil fuel utilization, economic growth and capital accumulation, while a population grows endogenously (blue lines), and when population growth is exogenous, and equals to 0.02% (red lines). The market-based approach has been applied for both scenarios.

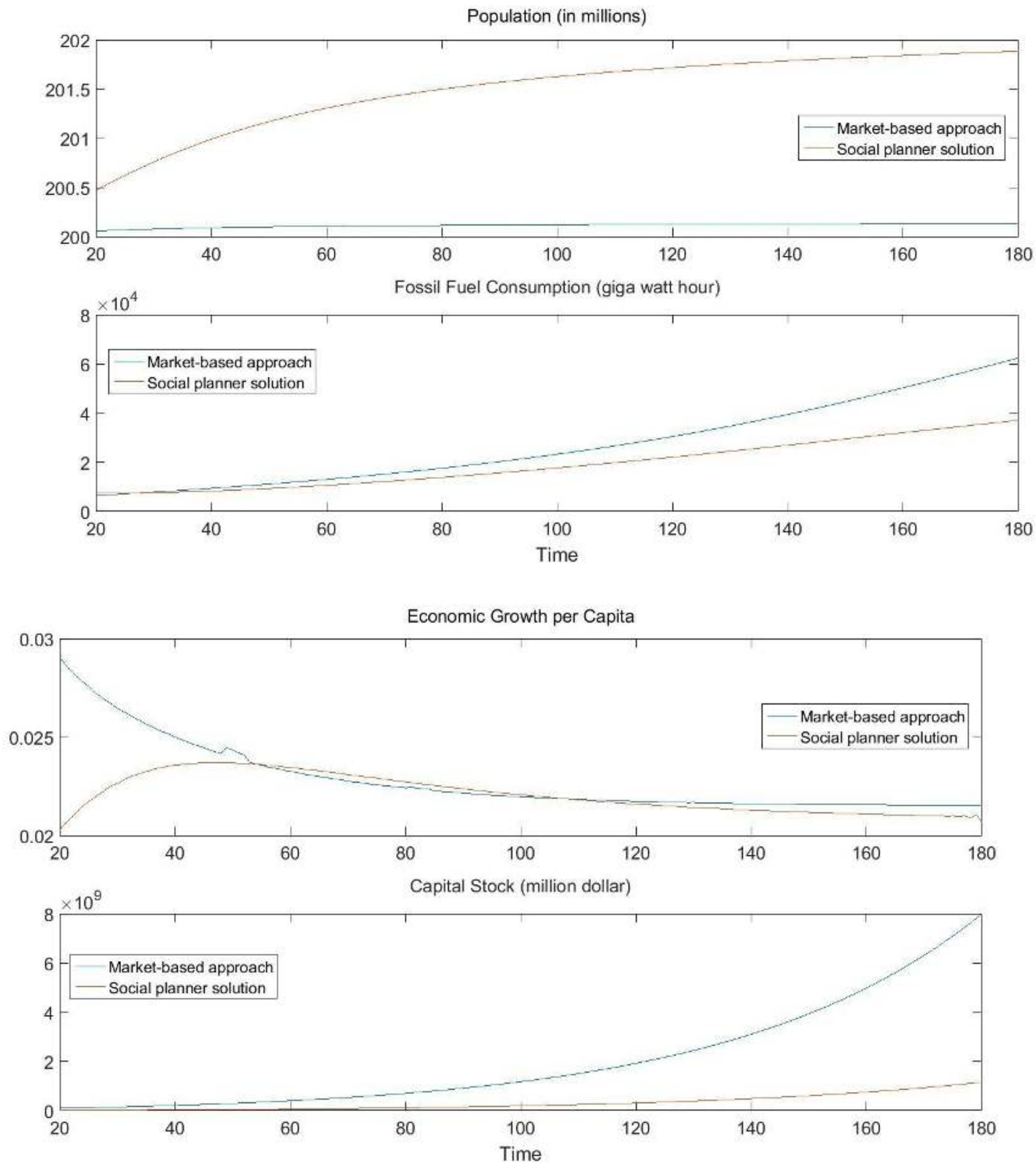


Figure 4: Endogenous population in the social planner versus the market-based approach.

Figure 4 shows population growth (the U.S. labor force), fossil fuel utilization, economic growth and capital accumulation for the market-based approach (blue lines) and social planner solution (red lines). The population grows endogenously in both cases.

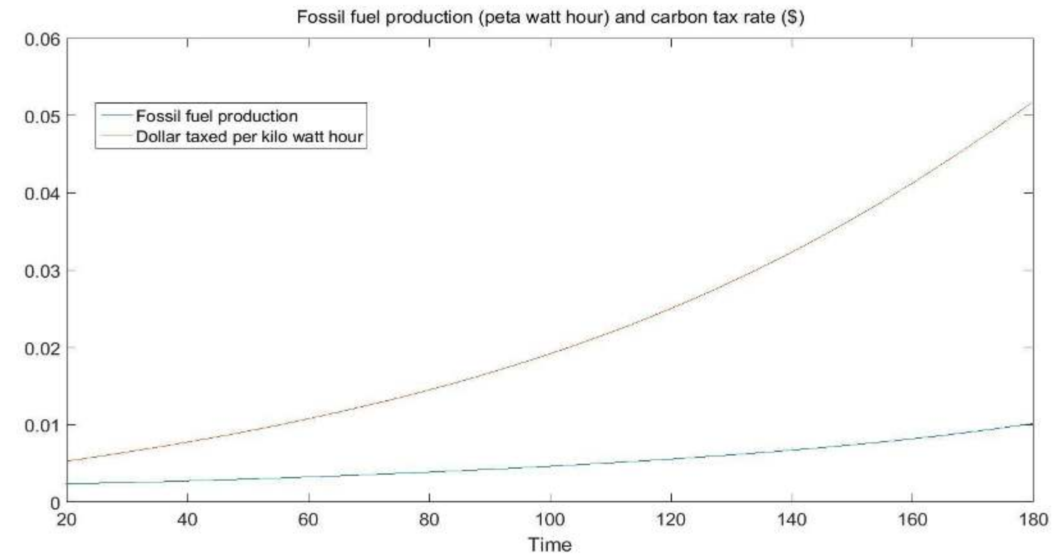


Figure 5-A: Carbon tax element on the fossil fuel utilization for the market-based approach.

Figure 5-A shows the fossil fuel production (per petawatt hour) and the tax rate (per kilowatt hour of energy production using fossil fuel resources) given the intervention in the market for the endogenous population.

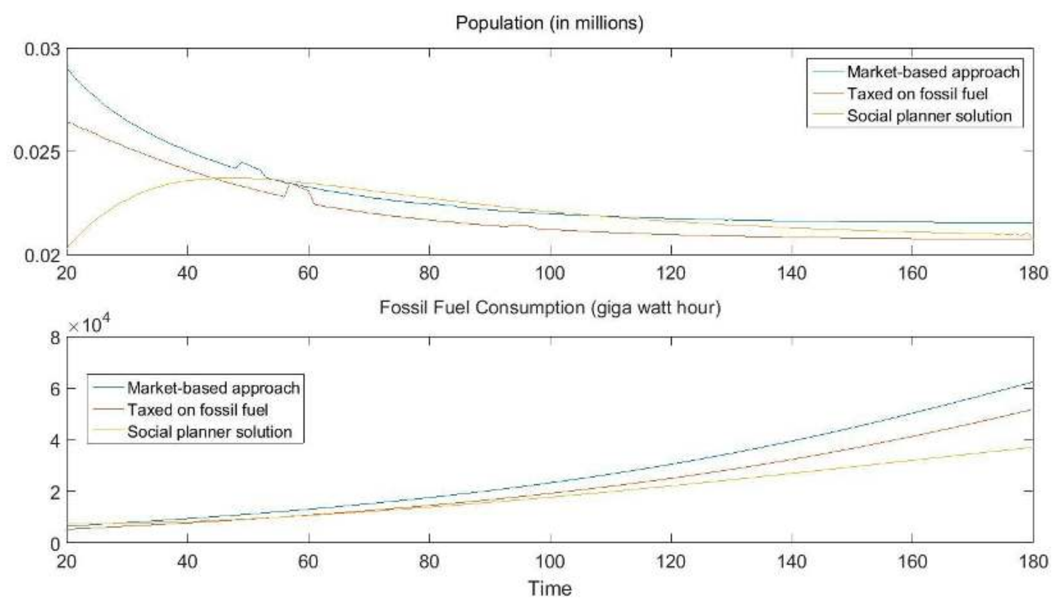


Figure 5-B: Comparison between the market-based approach, policy intervention on fossil fuel utilization, and social planner solution.

Figure 5-B shows economic growth and fossil fuel utilization when there is no intervention in the decentralized model (blue lines), while there exists a carbon-tax (red lines), and the social planner solution (yellow lines).

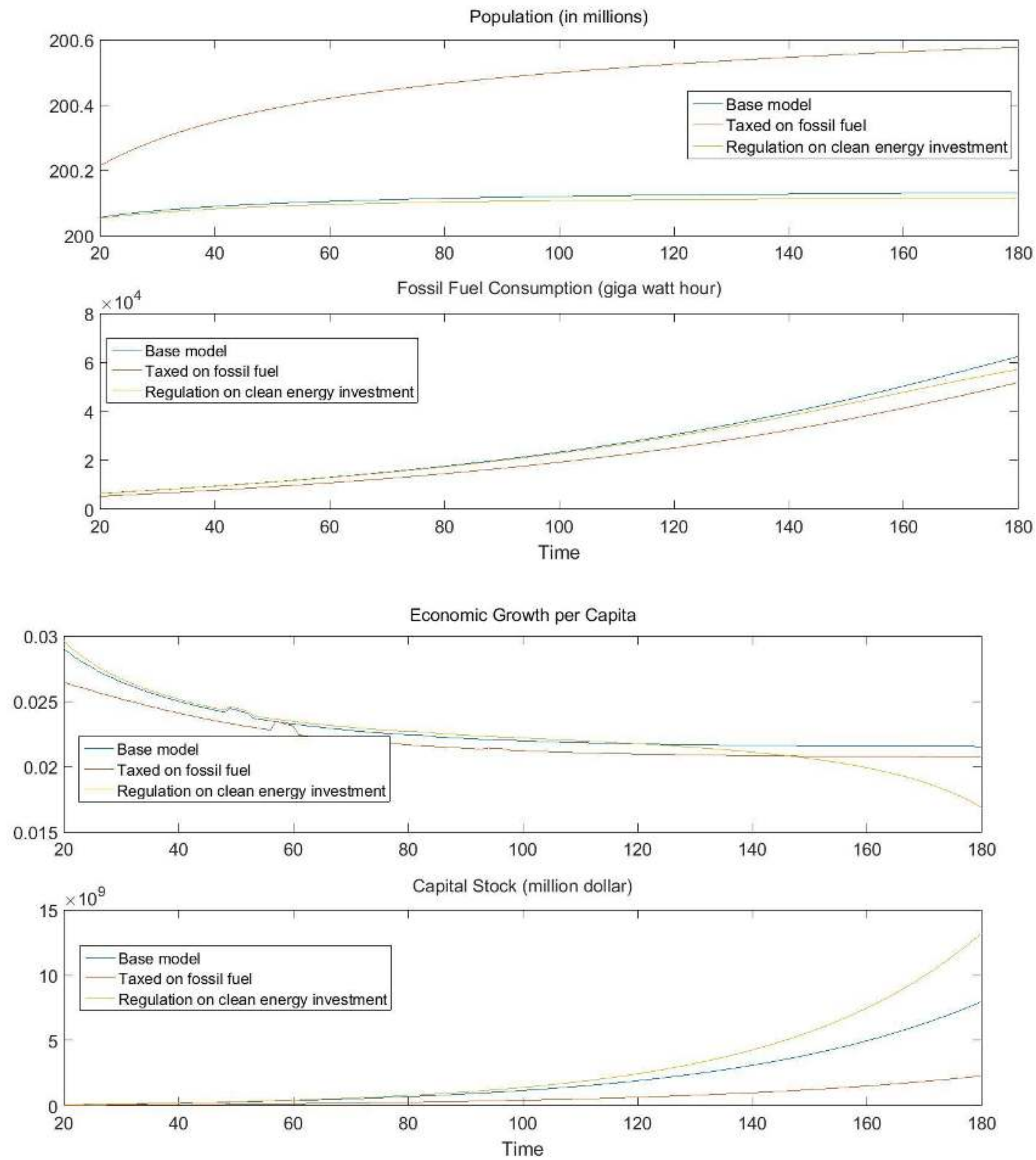


Figure 5-C: Comparison between base model and policy interventions on fossil fuel utilization.

Figure 5-C shows population growth (the U.S. labor force), fossil fuel utilization, economic growth and capital accumulation when there is no intervention in the market (blue lines), while there exists a carbon-tax (or tax on using fossil fuel energy), which decreases the profit in energy sectors to zero (red lines), and when government regulates the market by imposing a policy which requires firms to invest in clean energy production by 5% annually (yellow lines). All models are decentralized.

Table 1: Values of the parameters used in the model

Parameter	Value	Description
α	0.27	Capital share
γ	0.04	Energy share
ϑ	1.16	Fossil fuel impact on environment
θ	0.85	Clean energy technology impact on the new technology
ω	0.02	Researchers and financial impacts on the clean energy technology
ε_1	1.68	Income effect on the population growth
ε_2	2.16	Industrialization effect on the population growth
ρ	0.5	Substitution rate between clean energy and fossil fuel

Table 2: Initial values of the variables in the model

State variable	K (mil $)	PL (million)	TL (million)	FE (Gigawatthour)	$\overline{FE}$ (Gigawatthour)
$T_0 = 2012$	1.8e+7	1.9e+2	1.2	17,680	5,205,000

Table 3: Compensating variation* among different models

Moving away	To	Gain(+)/loss(-)
Social planner exogenous**	Market-based exogenous	-2.8%
Social planner endogenous***	Market-based endogenous	-3.3%
Market-based endogenous	Regulation on energy investment	-0.6%
Market-based endogenous	Taxed on fossil fuel	+2.3

* The CV measures the percent of consumption of individuals in one economy, who need to be compensated in order to give up living in that economy and move to another

** Exogenous population growth

*** Endogenous population growth

List of variables and parameters used in the model

U: Utility function

C: Consumption

Y: Production/income

K: Physical capital

I: Investment in physical capital

L: Total number of laborers in the economy (the summation of workers and researchers)

PL: Number of workers available in the production process

TL: Number of researchers available in producing technology (Jones, 2002, uses 0.036*L)

A: Technological progress in the production function

A_C: Required technology to utilize clean energy

N: Total population

CE: Clean energy

FE: Fossil fuel energy

E: Total energy consumption

ED: Environmental degradation, or damage function

P_{FE}: Price of fossil fuel energy use

P_{AC}: Price of clean energy use

WG: Compensation due to a change in individuals' consumption

β: Discount factor (0.96 is used vastly in the Macro literature)

δ: Capital depreciation, 0.03 has been used as a value in this research

ξ: Fraction of the population in the labor force based on the BLS is 0.63

α: Capital share in the production function (the range between 0.27 ~ 0.33 are used vastly in the Macro literature)

σ: Level of risk aversion of the agent

γ: Energy share in the production function (Krusell [2012] used 0.04)

ρ: Substitution rate between clean energy and fossil fuel energy (Popp [2004] used 0.49 in his model)

υ: Impact of the fossil fuel energy consumption on the environmental degradation

φ: Normalizing factor to keep the negative impact of FE on the production less than one

ω: Impact of researchers on the production of clean energy technology (Jones [2002] used 0.015)

θ: Impact of the old clean energy technology on new technology (Jones [2002] used 0.94)

ε_1: Per capita income effect on the population growth (Cigno [1981] did not use any value since it was purely a theory-based paper)

ε_2: Effect of the level of industrialization on the population growth

ε: Error term in stochastic shocks of technology in the production function which is normally distributed with the mean zero and standard deviation of σ

$\bar{A}$: Constant growth for technological progress in the production function

$\bar{L}$: Constant population growth (based on the average population growth in the U.S.)

A_{C0}: Residuals in the equation explaining the technology for utilizing clean energy

Data calibration

To estimate the parameters of Equation 7, I used the time series for the US data. The main equation according to the model is: $\mathrm{ED_t} = 1 - \frac{\mathrm{FE_t}^{\vartheta}}{\varphi}$. Therefore, the estimating equation is given by:

$$\log(y_t) = \beta_1 + \beta_2 \log(FE_t) + \varepsilon_t \quad \text{(B1)}$$

where $y_t = 1 - ED_t$, $\beta_2 = -\vartheta$ and $\beta_1 = \vartheta\log(\varphi)$, $\varepsilon_t = \rho\varepsilon_{t-1} + \epsilon_t$

The table below shows the results. The error terms are serially correlated. To estimate the above model, I used the generalized least-squares method to estimate the parameters in a linear regression analysis in which the errors are serially correlated. Specifically, the errors are assumed to follow a first-order autoregressive process. Based on the above estimation, we get the below values for the estimated parameters: $\vartheta = 1.162$ and $\varphi = 197738.7$

Table 4: Estimating the parameters in Equation 7

LED	Coef	Std. Err.	t-stat	P > | t |
LEF	-1.1616	0.2812	-4.13	0.000
Cons	14.1654	3.0871	4.59	0.000
R-square	0.967			

LED = log of biocapacity index as a proxy for environmental degradation

LFE = log of fossil fuel energy production, trillion BTU

To derive the values of parameters in Equation 8 [$AC_{t+1} = AC_0 AC_t^{\theta}(TL_t TY_t)^{\omega}$], we can use the following values for θ and ω based on Jones' (2002) calibration: $\theta = 0.94$ and $\omega = 0.015$. However, I changed the model by entering the interaction of financing the technology; therefore, it is advantageous to estimate it as follows:

$$\log(AC_{t+1}) = \log(AC_0) + \theta\log(AC_t) + \omega\log(TL_t * TY_t) + \epsilon_t \quad \text{(B2)}$$

Table 5: Estimating the parameters in Equation 8

LACP	Coef	Std. Err.	t-stat	P > | t |
LAC	0.844	0.0203	41.49	0.000
LTYL	0.022	0.0045	4.90	0.000
LAC0 (Cons)	1.159	0.2855	4.06	0.001
R-square	0.957			

LACP= log of technology of clean energy utilization for the next period

LAC= log of technology of clean energy utilization

LTYL= log of the interaction between TL and TY (number of the researchers in the economy and the required resources to finance the technology)

Based on the above estimation, we get the below values for the estimated parameters: $\theta = 0.84$ and $\omega = 0.02$ which is similar to the Jones' original calibration.

To estimate Equation 15 parameters, I need to use time series again. The main equation according to the model is: $L_{t+1} = L_t + L_0({}^{Y_t}/_{L_t})^{\varepsilon_1}({}^{L_t}/_{K_t})^{\varepsilon_2}$

Therefore, the estimating equation is defined as:

$$\log(g_{L_t}) = \varepsilon_0 + \varepsilon_1 \log(Y_t/L_t) + \varepsilon_2 \log(L_t/K_t) + \varepsilon_t \quad \text{(B3)}$$

where $\varepsilon_0 = \log(L_0)$ and g is the growth rate, rearrange the above equation for L, we get:

$$\log(g_{L_t}) = \varepsilon_0 + \varepsilon_1 \log(Y_t) + \varepsilon'_2 \log(K_t) + \varepsilon'' \log(L_t) + \varepsilon_t \quad \text{(B4)}$$

where $\varepsilon'_2 = -\varepsilon_2$ and $\varepsilon'' = \varepsilon_2 - \varepsilon_1$

Table 6: Estimating the parameters in Equation 15

LGN	Coef	Std. Err.	t-stat	P > | t |
LY	1.679	0.18	9.31	0.000
LK	-2.163	0.213	-10.16	0.000
LL	0.485	0.056	8.65	0.000
Cons	0.856	0.624	1.37	0.182
R-square	0.988			

LGN= log of population growth

LY= log of Y (GDP) (1.895)

LK= log of K (physical capital) (-2.11)

LL = log of L (labor force) (0.215)   Cons (17.354) (L0=3.4E+7)

Based on the above regression, the estimated parameters are:

$\varepsilon_1 = 1.679$, $\varepsilon_2 = 2.163$ and $L_0 = 2.353$.

Solving the F.O.C's for both social planner and market-based approaches

Solving the social planner's F.O.C [exogenous population]

$$Y_t = (1 - \frac{FE_t{}^{\vartheta}}{\varphi})[A_t K_t^{\alpha} PL_t^{1-\alpha-\gamma}[(AC_t CE)^{\rho} + FE_t^{\rho}]^{\gamma/\rho}] \quad \text{(C1)}$$

$$\left(1 - \frac{FE_t{}^{\vartheta}}{\varphi}\right)\left(A_t K_t^{\alpha} PL_t^{1-\alpha-\gamma}\right)\left((AC_t CE)^{\rho} + FE_t^{\rho}\right)^{\gamma/\rho} = C_t + K_{t+1} - (1-\delta)K_t +$$
$$\left(P_0 + P_1 (\sum_{i=1}^{t} FE_i / \overline{FE})^{P_2} + P_3 (FE_t / \overline{CTE})^{P_4}\right) FE_t + TY_t$$

(C2)

$$\left(1 - \frac{FE_t{}^{\vartheta}}{\varphi}\right)(A_t K_t^{\alpha} (l_{PL} L_t)^{1-\alpha-\gamma})\left((AC_t CE)^{\rho} + FE_t^{\rho}\right)^{\gamma/\rho} = C_t + K_{t+1} - (1-\delta)K_t +$$
$$\left(P_0 + P_1 (\sum_{i=1}^{t} FE_i / \overline{FE})^{P_2} + P_3 (FE_t / \overline{CTE})^{P_4}\right) FE_t + TY_t \quad \text{(C3)}$$

$$AC_{t+1} = AC_0 AC_t^{\theta} (l_{PL} L_t TY_t)^{\omega} \quad \text{(C4)}$$

Solving the Euler equations for the social planner when the population is exogenous

First-order conditions are:

$$\{C_t\}: \beta^t \frac{C_t^{-\sigma}}{L_t^{1-\sigma}} = \lambda_{1t} \quad \text{(C5)}$$

$$\{K_{t+1}\}: \lambda_{1t+1}\{\alpha\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)(A_{t+1}K_{t+1}^{\alpha-1}(l_{PL}L_{t+1})^{1-\alpha-\gamma})\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho}+1-\delta\}=\lambda_{1t}$$

(C6)

$$\{FE_t\}: \left(1-\frac{FE_t}{\varphi}^{\vartheta}\right)(A_tK_t^{\alpha}(l_{PL}L_t)^{1-\alpha-\gamma})\gamma FE_t^{\rho-1}\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma/\rho-1}-\frac{\vartheta}{\varphi}\frac{FE_t}{\varphi}^{\vartheta-1}(A_tK_t^{\alpha}(l_{PL}L_t)^{1-\alpha-\gamma})\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma/\rho}-\left(P_0+P_1(\sum_{i=1}^{t}FE_i/\overline{FE})^{P_2}+P_3(FE_t/\overline{CTE})^{P_4}+(\frac{P_1P_2}{\overline{FE}}\left(\sum_{i=1}^{t}FE_i/\overline{FE}\right)^{P_2-1}+\frac{P_3P_4}{\overline{CTE}}(FE_t/\overline{CTE})^{P_4-1})FE_t\right)=0 \quad \text{(C7)}$$

$$\{AC_{t+1}\}: \lambda_{2t+1}\{\theta AC_0AC_{t+1}^{\theta-1}(l_{TL}L_{t+1}TY_{t+1})^{\omega}\}+\lambda_{1t+1}\left\{\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\gamma CE^{\rho}AC_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho-1}\right\}=\lambda_{2t} \quad \text{(C8)}$$

$$\{TY_t\}: \lambda_{1t}=\lambda_{2t}[\omega AC_0AC_t^{\theta}(l_{TL}L_t)^{\omega}TY_t^{\omega-1}] \quad \text{(C9)}$$

Substituting Equations 58 and 62 (and the updated forms of them) in the above F.O.Cs, we get the following Euler equations:

$$\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\{\alpha\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)(A_{t+1}K_{t+1}^{\alpha-1}(l_{PL}L_{t+1})^{1-\alpha-\gamma})\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho}+1-\delta\}=\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}$$

(C10)

And the above equation, when there is no fossil fuel energy left to use, is:

$$\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\{\alpha(A_{t+1}K_{t+1}^{\alpha-1}(l_{PL}L_{t+1})^{1-\alpha-\gamma})(AC_{t+1}CE)^{\gamma}+1-\delta\}=\frac{C_t^{-\sigma}}{L_t^{1-\sigma}} \quad \text{(C11)}$$

$$\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)(A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma})\gamma FE_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho-1}=$$

$$\frac{\vartheta}{\varphi}\frac{FE_{t+1}}{\varphi}^{\vartheta-1}(A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma})\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho}+P_0+P_1(\sum_{i=1}^{t+1}FE_i/\overline{FE})^{P_2}+$$

$$P_3(FE_t/\overline{CTE})^{P_4}+(\frac{P_1P_2}{\overline{FE}}\left(\sum_{i=1}^{t+1}FE_i/\overline{FE}\right)^{P_2-1}+\frac{P_3P_4}{\overline{CTE}}(FE_{t+1}/\overline{CTE})^{P_4-1})FE_{t+1} \quad \text{(C12)}$$

$$\frac{\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}}{\omega AC_0AC_{t+1}^{\theta}(l_{TL}L_{t+1})^{\omega}TY_{t+1}^{\omega-1}}\left\{\theta AC_0AC_{t+1}^{\theta-1}(l_{TL}L_{t+1}TY_{t+1})^{\omega}\right\}+\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\left\{\left(1-\right.\right.$$

$$\left.\left.\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\gamma CE^{\rho}AC_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho-1}\right\}=$$

$$\frac{\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}}{\omega AC_0AC_t^{\theta}(l_{TL}L_t)^{\omega}TY_t^{\omega-1}} \quad \text{(C13)}$$

And the above equation, when no fossil fuel energy remains, is:

$$\frac{\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}}{\omega AC_0AC_{t+1}^{\theta}(l_{TL}L_{t+1})^{\omega}TY_{t+1}^{\omega-1}}\left\{\theta AC_0AC_{t+1}^{\theta-1}(l_{TL}L_{t+1}TY_{t+1})^{\omega}\right\}+$$

$$\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\{A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\gamma CE(AC_{t+1}CE)^{\gamma-1}\}=\frac{\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}}{\omega AC_0AC_t^{\theta}(l_{TL}L_t)^{\omega}TY_t^{\omega-1}} \quad \text{(C14)}$$

Solving the social planner's F.O.C [endogenous population])

By solving the Euler equations for the social planner when the population is endogenous, the first-order conditions are:

$$\{C_t\}: \beta^t\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}=\lambda_{1t} \quad \text{(C15)}$$

$$\{L_{t+1}\}: -\beta^{t+1}C_{t+1}^{1-\sigma}L_{t+1}^{\sigma-2} + \lambda_{1t+1}\Big\{(1-\alpha-\gamma)\Big(1 - \frac{FE_{t+1}}{\varphi}^{\vartheta}\Big)(A_{t+1}K_{t+1}^{\alpha}(l_{PL})^{1-\alpha-\gamma}(L_{t+1})^{-\alpha-\gamma})\big((AC_{t+1}CE)^{\rho} + FE_{t+1}^{\rho}\big)^{\gamma/\rho}\Big\} + \lambda_{2t+1}\{\omega AC_0 AC_{t+1}^{\theta}(l_{TL}TY_{t+1})^{\omega}L_{t+1}^{\omega-1}\} + \lambda_{3t+1}\Big\{L_0(\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1)\Big(1 - \frac{FE_{t+1}}{\varphi}^{\vartheta}\Big)^{\varepsilon_1} A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1-1}\big((AC_{t+1}CE)^{\rho} + FE_{t+1}^{\rho}\big)^{\gamma\varepsilon_1/\rho} + 1\Big\} = \lambda_{3t} \quad \text{(C16)}$$

$$\{K_{t+1}\}: \lambda_{1t+1}\Big\{\Big(1 - \frac{FE_{t+1}}{\varphi}^{\vartheta}\Big)\alpha(A_{t+1}K_{t+1}^{\alpha-1}(l_{PL}L_{t+1})^{1-\alpha-\gamma})\big((AC_{t+1}CE)^{\rho} + FE_{t+1}^{\rho}\big)^{\gamma/\rho} + 1 - \delta\Big\} + \lambda_{3t+1}\{(\alpha\varepsilon_1-\varepsilon_2)L_0\Big(1 - \frac{FE_{t+1}}{\varphi}^{\vartheta}\Big)^{\varepsilon_1} A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2-1}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\big((AC_{t+1}CE)^{\rho} + FE_{t+1}^{\rho}\big)^{\gamma\varepsilon_1/\rho} = \lambda_{1t} \quad \text{(C17)}$$

$$\{FE_t\}: \lambda_{1t}\Big\{\Big(1 - \frac{FE_t}{\varphi}^{\vartheta}\Big)(A_tK_t^{\alpha}(l_{PL}L_t)^{1-\alpha-\gamma})\gamma FE_t^{\rho-1}\big((AC_tCE)^{\rho} + FE_t^{\rho}\big)^{\gamma/\rho-1} - \frac{\vartheta}{\varphi}\frac{FE_t}{\varphi}^{\vartheta-1}(A_tK_t^{\alpha}(l_{PL}L_t)^{1-\alpha-\gamma})\big((AC_tCE)^{\rho} + FE_t^{\rho}\big)^{\gamma/\rho} - \Big(P_0 + P_1(\textstyle\sum_{i=1}^{t} FE_i/\overline{FE})^{P_2} + P_3(FE_t/\overline{CTE})^{P_4} + (\frac{P_1P_2}{\overline{FE}}\Big(\textstyle\sum_{i=1}^{t} FE_i/\overline{FE}\Big)^{P_2-1} + \frac{P_3P_4}{\overline{CTE}}(FE_t/\overline{CTE})^{P_4-1})FE_t\Big)\Big\} + \lambda_{3t}\{L_0\Big(1 - \frac{FE_t}{\varphi}^{\vartheta}\Big)^{\varepsilon_1} A_t^{\varepsilon_1}K_t^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_t^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\gamma\varepsilon_1 FE_t^{\rho-1}\big((AC_tCE)^{\rho} + FE_t^{\rho}\big)^{\gamma\varepsilon_1/\rho-1} - L_0\frac{\vartheta\varepsilon_1}{\varphi}\frac{FE_t}{\varphi}^{\vartheta-1}\Big(1 - \frac{FE_t}{\varphi}^{\vartheta}\Big)^{\varepsilon_1-1} A_t^{\varepsilon_1}K_t^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_t^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1+1}\big((AC_tCE)^{\rho} + FE_t^{\rho}\big)^{\gamma\varepsilon_1/\rho}\} = 0 \quad \text{(C18)}$$

$$\{AC_{t+1}\}: \lambda_{1t+1}\left\{\left(1-\frac{FE_{t+1}{}^{\vartheta}}{\varphi}\right)A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\gamma CE^{\rho}AC_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho-1}\right\}+\lambda_{2t+1}\{\theta AC_0 AC_{t+1}^{\theta-1}(l_{TL}L_{t+1}TY_{t+1})^{\omega}\}+\lambda_{3t+1}\{\gamma\varepsilon_1 CE^{\rho}AC_{t+1}^{\rho-1}L_0\left(1-\frac{FE_{t+1}{}^{\vartheta}}{\varphi}\right)^{\varepsilon_1}A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho-1}\}=\lambda_{2t}$$

(C19)

$$\{TY_t\}: \lambda_{1t}=\lambda_{2t}[\omega AC_0 AC_t^{\theta}(l_{TL}L_t)^{\omega}TY_t^{\omega-1}]$$

(C20)

Substituting Equations 68 and 73 (and the updated forms of them) in the above F.O.Cs, we get the following equations:

$$-\beta^{t+1}C_{t+1}^{1-\sigma}L_{t+1}^{\sigma-2}+\beta^{t+1}\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\left\{(1-\alpha-\gamma)\left(1-\frac{FE_{t+1}{}^{\vartheta}}{\varphi}\right)(A_{t+1}K_{t+1}^{\alpha}(l_{PL})^{1-\alpha-\gamma}(L_{t+1})^{-\alpha-\gamma})\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho}\right\}+\frac{\beta^{t+1}\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}}{\omega AC_0 AC_{t+1}^{\theta}(l_{TL}L_{t+1})^{\omega}TY_{t+1}^{\omega-1}}\{\omega AC_0 AC_{t+1}^{\theta}(l_{TL}TY_{t+1})^{\omega}L_{t+1}^{\omega-1}\}+\lambda_{3t+1}\left\{L_0(\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1)\left(1-\frac{FE_{t+1}{}^{\vartheta}}{\varphi}\right)^{\varepsilon_1}A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho}+1\right\}=\lambda_{3t}$$

(C21)

$$\beta^{t+1}\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\left\{\left(1-\frac{FE_{t+1}{}^{\vartheta}}{\varphi}\right)\alpha(A_{t+1}K_{t+1}^{\alpha-1}(l_{PL}L_{t+1})^{1-\alpha-\gamma})\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho}+1-\delta\right\}+\lambda_{3t+1}\{(\alpha\varepsilon_1-\varepsilon_2)L_0\left(1-\frac{FE_{t+1}{}^{\vartheta}}{\varphi}\right)^{\varepsilon_1}A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2-1}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho}=\beta^{t}\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}$$

(C22)

$$\beta^t \frac{C_t^{-\sigma}}{L_t^{1-\sigma}}\Bigg\{\left(1-\frac{FE_t{}^{\vartheta}}{\varphi}\right)(A_t K_t^{\alpha}(l_{PL}L_t)^{1-\alpha-\gamma})\gamma FE_t^{\rho-1}\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma/\rho-1}-$$

$$\frac{\vartheta}{\varphi}\frac{FE_t{}^{\vartheta-1}}{\varphi}(A_t K_t^{\alpha}(l_{PL}L_t)^{1-\alpha-\gamma})\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma/\rho}-\Bigg(P_0+P_1\left(\sum_{i=1}^{t}FE_i\Big/\overline{FE}\right)^{P_2}+$$

$$P_3\left(FE_t\Big/\overline{CTE}\right)^{P_4}+\left(\frac{P_1P_2}{\overline{FE}}\left(\sum_{i=1}^{t}FE_i\Big/\overline{FE}\right)^{P_2-1}+\frac{P_3P_4}{\overline{CTE}}\left(FE_t\Big/\overline{CTE}\right)^{P_4-1}\right)FE_t\Bigg)\Bigg\}+\ \lambda_{3t}\{L_0\Bigg(1-$$

$$\frac{FE_t{}^{\vartheta}}{\varphi}\Bigg)^{\varepsilon_1}A_t^{\varepsilon_1}K_t^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_t^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\gamma\varepsilon_1 FE_t^{\rho-1}\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma\varepsilon_1/\rho-1}-$$

$$L_0\frac{\vartheta\varepsilon_1}{\varphi}\frac{FE_t{}^{\vartheta-1}}{\varphi}\left(1-\frac{FE_t{}^{\vartheta}}{\varphi}\right)^{\varepsilon_1-1}A_t^{\varepsilon_1}K_t^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_t^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma\varepsilon_1/\rho}\}=0$$

(C23)

$$\beta^{t+1}\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\left\{\left(1-\frac{FE_{t+1}{}^{\vartheta}}{\varphi}\right)A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\gamma CE^{\rho}AC_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho-1}\right\}+$$

$$\frac{\beta^{t+1}\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}}{\omega AC_0AC_{t+1}^{\theta}(l_{TL}L_{t+1})^{\omega}TY_{t+1}^{\omega-1}}\{\theta AC_0AC_{t+1}^{\theta-1}(l_{TL}L_{t+1}TY_{t+1})^{\omega}\}+\lambda_{3t+1}\{\gamma\varepsilon_1CE^{\rho}AC_{t+1}^{\rho-1}L_0\Bigg(1-$$

$$\frac{FE_{t+1}{}^{\vartheta}}{\varphi}\Bigg)^{\varepsilon_1}A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho-1}\}=$$

$$\frac{\beta^{t}\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}}{\omega AC_0AC_t^{\theta}(l_{TL}L_t)^{\omega}TY_t^{\omega-1}}$$

(C24)

Now, we rearrange Equation 75 for λ_{3t}, update it to get λ_{3t+1}, and replace it back into Equations 74, 75 and 77, having our three Euler equations as follows:

$$-\beta C_{t+1}^{1-\sigma}L_{t+1}^{\sigma-2}+\ \beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\Bigg\{(1-\alpha-\gamma)\Bigg(1-$$

$$\frac{FE_{t+1}{}^{\vartheta}}{\varphi}\Bigg)(A_{t+1}K_{t+1}^{\alpha}(l_{PL})^{1-\alpha-\gamma}(L_{t+1})^{-\alpha-\gamma})\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho}\Bigg\}+$$

$$\frac{\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}}{\omega AC_0AC_{t+1}^{\theta}(l_{TL}L_{t+1})^{\omega}TY_{t+1}^{\omega-1}}\{\omega AC_0AC_{t+1}^{\theta}(l_{TL}TY_{t+1})^{\omega}L_{t+1}^{\omega-1}\}+\frac{AA}{BB}*\Big\{L_0(\varepsilon_2-\alpha\varepsilon_1-$$

$$\gamma\varepsilon_1)\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)^{\varepsilon_1} A_{t+1}^{\varepsilon_1} K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2} l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma} L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho}+1\Big\}=\frac{CC}{DD}$$

(C25)

$$AA=-\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\Big\{\left(\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)(A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma})\gamma FE_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho-1}-\right.$$

$$\frac{\vartheta}{\varphi}\frac{FE_{t+1}}{\varphi}^{\vartheta-1}(A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma})\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho}-\Big(P_0+P_1(\textstyle\sum_{i=1}^{t+1}FE_i\big/\overline{FE})^{P_2}+$$

$$P_3(FE_{t+1}\big/\overline{CTE})^{P_4}+(\frac{P_1P_2}{\overline{FE}}\left(\textstyle\sum_{i=1}^{t+1}FE_i\big/\overline{FE}\right)^{P_2-1}+\frac{P_3P_4}{\overline{CTE}}(FE_{t+1}\big/\overline{CTE})^{P_4-1})FE_{t+1}\Big)\Big)\Big\}$$

$$BB=\Big\{L_0\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)^{\varepsilon_1} A_{t+1}^{\varepsilon_1} K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2} l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma} L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\gamma\varepsilon_1 FE_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+\right.$$

$$\left.FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho-1}-L_0\frac{\vartheta\varepsilon_1}{\varphi}\frac{FE_{t+1}}{\varphi}^{\vartheta-1}\Big(1-$$

$$\frac{FE_{t+1}}{\varphi}^{\vartheta}\Big)^{\varepsilon_1-1} A_{t+1}^{\varepsilon_1} K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2} l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma} L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho}\Big\}$$

$$CC=-\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}\Big\{\left(\left(1-\frac{FE_t}{\varphi}^{\vartheta}\right)(A_tK_t^{\alpha}(l_{PL}L_t)^{1-\alpha-\gamma})\gamma FE_t^{\rho-1}\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma/\rho-1}-\right.$$

$$\frac{\vartheta}{\varphi}\frac{FE_t}{\varphi}^{\vartheta-1}(A_tK_t^{\alpha}(l_{PL}L_t)^{1-\alpha-\gamma})\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma/\rho}-\Big(P_0+P_1(\textstyle\sum_{i=1}^{t}FE_i\big/\overline{FE})^{P_2}+$$

$$P_3(FE_t\big/\overline{CTE})^{P_4}+(\frac{P_1P_2}{\overline{FE}}\left(\textstyle\sum_{i=1}^{t}FE_i\big/\overline{FE}\right)^{P_2-1}+\frac{P_3P_4}{\overline{CTE}}(FE_t\big/\overline{CTE})^{P_4-1})FE_t\Big)\Big)\Big\}$$

$$DD=\{L_0\left(1-\frac{FE_t}{\varphi}^{\vartheta}\right)^{\varepsilon_1} A_t^{\varepsilon_1} K_t^{\alpha\varepsilon_1-\varepsilon_2} l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma} L_t^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\gamma\varepsilon_1 FE_t^{\rho-1}\left((AC_tCE)^{\rho}+FE_t^{\rho}\right)^{\gamma\varepsilon_1/\rho-1}-$$

$$L_0\frac{\vartheta\varepsilon_1}{\varphi}\frac{FE_t}{\varphi}^{\vartheta-1}\left(1-\frac{FE_t}{\varphi}^{\vartheta}\right)^{\varepsilon_1-1} A_t^{\varepsilon_1} K_t^{\alpha\varepsilon_1-\varepsilon_2} l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma} L_t^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}$$

And the above equation, when there is no fossil fuel energy left to use, is:

$$-\beta^2 C_{t+1}^{1-\sigma} L_{t+1}^{\sigma-2} + \beta^2 \frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}} \{(1-\alpha-\gamma)(A_{t+1} K_{t+1}^{\alpha} (l_{PL})^{1-\alpha-\gamma} (L_{t+1})^{-\alpha-\gamma})(AC_{t+1} CE)^{\gamma}\} +$$

$$\frac{\beta^2 \frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}}{\omega AC_0 AC_{t+1}^{\theta} (l_{TL} L_{t+1})^{\omega} TY_{t+1}^{\omega-1}} \{\omega AC_0 AC_{t+1}^{\theta} (l_{TL} TY_{t+1})^{\omega} L_{t+1}^{\omega-1}\} +$$

$$\frac{\beta \frac{C_t^{-\sigma}}{L_t^{1-\sigma}} - \beta^2 \frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}} (\alpha (A_{t+1} K_{t+1}^{\alpha-1} (l_{PL} L_{t+1})^{1-\alpha-\gamma})(AC_{t+1} CE)^{\gamma} + 1 - \delta)}{(\alpha\varepsilon_1 - \varepsilon_2) L_0 A_{t+1}^{\varepsilon_1} K_{t+1}^{\alpha\varepsilon_1 - \varepsilon_2 - 1} l_{PL}^{\varepsilon_1 - \alpha\varepsilon_1 - \varepsilon_1\gamma} L_{t+1}^{\varepsilon_2 - \alpha\varepsilon_1 - \gamma\varepsilon_1} (AC_{t+1} CE)^{\gamma\varepsilon_1}} * \{L_0(\varepsilon_2 - \alpha\varepsilon_1 -$$

$$\gamma\varepsilon_1) A_{t+1}^{\varepsilon_1} K_{t+1}^{\alpha\varepsilon_1 - \varepsilon_2} l_{PL}^{\varepsilon_1 - \alpha\varepsilon_1 - \varepsilon_1\gamma} L_{t+1}^{\varepsilon_2 - \alpha\varepsilon_1 - \gamma\varepsilon_1 - 1} (AC_{t+1} CE)^{\gamma\varepsilon_1} + 1\} =$$

$$\frac{\frac{C_{t-1}^{-\sigma}}{L_{t-1}^{1-\sigma}} - \beta \frac{C_t^{-\sigma}}{L_t^{1-\sigma}} (\alpha (A_t K_t^{\alpha-1} (l_{PL} L_t)^{1-\alpha-\gamma})(AC_t CE)^{\gamma} + 1 - \delta)}{(\alpha\varepsilon_1 - \varepsilon_2) L_0 A_t^{\varepsilon_1} K_t^{\alpha\varepsilon_1 - \varepsilon_2 - 1} l_{PL}^{\varepsilon_1 - \alpha\varepsilon_1 - \varepsilon_1\gamma} L_t^{\varepsilon_2 - \alpha\varepsilon_1 - \gamma\varepsilon_1} (AC_t CE)^{\gamma\varepsilon_1}} \quad \text{(C26)}$$

$$\beta \frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}} \left\{ \left(1 - \frac{FE_{t+1}}{\varphi}^{\vartheta}\right) \alpha (A_{t+1} K_{t+1}^{\alpha-1} (l_{PL} L_{t+1})^{1-\alpha-\gamma}) \left((AC_{t+1} CE)^{\rho} + FE_{t+1}^{\rho}\right)^{\gamma/\rho} + 1 - \delta \right\} +$$

$$\left(\frac{EE}{FF}\right) \{(\alpha\varepsilon_1 - \varepsilon_2) L_0 \left(1 - \frac{FE_{t+1}}{\varphi}^{\vartheta}\right)^{\varepsilon_1} A_{t+1}^{\varepsilon_1} K_{t+1}^{\alpha\varepsilon_1 - \varepsilon_2 - 1} l_{PL}^{\varepsilon_1 - \alpha\varepsilon_1 - \varepsilon_1\gamma} L_{t+1}^{\varepsilon_2 - \alpha\varepsilon_1 - \gamma\varepsilon_1} \big((AC_{t+1} CE)^{\rho} +$$

$$FE_{t+1}^{\rho}\big)^{\gamma\varepsilon_1/\rho} = \frac{C_t^{-\sigma}}{L_t^{1-\sigma}} \quad \text{(C27)}$$

$$EE = -\beta \frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}} \left\{ \left(1 - \frac{FE_{t+1}}{\varphi}^{\vartheta}\right) (A_{t+1} K_{t+1}^{\alpha} (l_{PL} L_{t+1})^{1-\alpha-\gamma}) \gamma FE_{t+1}^{\rho-1} \left((AC_{t+1} CE)^{\rho} + FE_{t+1}^{\rho}\right)^{\gamma/\rho - 1} - \right.$$

$$\frac{\vartheta}{\varphi} \frac{FE_{t+1}}{\varphi}^{\vartheta-1} (A_{t+1} K_{t+1}^{\alpha} (l_{PL} L_{t+1})^{1-\alpha-\gamma}) \left((AC_{t+1} CE)^{\rho} + FE_{t+1}^{\rho}\right)^{\gamma/\rho} - \Bigg(P_0 + P_1 \Big(\sum_{i=1}^{t+1} FE_i \Big/ \overline{FE}\Big)^{P_2} +$$

$$\left. P_3 \Big(FE_{t+1} \Big/ \overline{CTE}\Big)^{P_4} + \Big(\frac{P_1 P_2}{\overline{FE}} \left(\sum_{i=1}^{t+1} FE_i \Big/ \overline{FE}\right)^{P_2 - 1} + \frac{P_3 P_4}{\overline{CTE}} \Big(FE_{t+1} \Big/ \overline{CTE}\Big)^{P_4 - 1}\Big) FE_{t+1} \Bigg) \right\}$$

$$FF=\left\{L_0\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)^{\varepsilon_1} A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\gamma\varepsilon_1 FE_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho-1}-L_0\frac{\vartheta\varepsilon_1}{\varphi}\frac{FE_{t+1}}{\varphi}^{\vartheta-1}\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)^{\varepsilon_1-1} A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho}\right\}$$

$$\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\left\{\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\gamma CE^{\rho}AC_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho-1}\right\}+\frac{\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}}{\omega AC_0AC_{t+1}^{\theta}(l_{TL}L_{t+1})^{\omega}TY_{t+1}^{\omega-1}}\left\{\theta AC_0AC_{t+1}^{\theta-1}(l_{TL}L_{t+1}TY_{t+1})^{\omega}\right\}+\left(\frac{GG}{HH}\right)\left\{\gamma\varepsilon_1 CE^{\rho}AC_{t+1}^{\rho-1}L_0\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)^{\varepsilon_1} A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho-1}\right\}=\frac{\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}}{\omega AC_0AC_t^{\theta}(l_{TL}L_t)^{\omega}TY_t^{\omega-1}} \tag{C28}$$

$$GG=-\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\left\{\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)\left(A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\right)\gamma FE_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho-1}-\frac{\vartheta}{\varphi}\frac{FE_{t+1}}{\varphi}^{\vartheta-1}\left(A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\right)\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma/\rho}-\left(P_0+P_1\left(\sum_{i=1}^{t+1}FE_i\Big/\overline{FE}\right)^{P_2}+P_3\left(FE_{t+1}\Big/\overline{CTE}\right)^{P_4}+\left(\frac{P_1P_2}{\overline{FE}}\left(\sum_{i=1}^{t+1}FE_i\Big/\overline{FE}\right)^{P_2-1}+\frac{P_3P_4}{\overline{CTE}}\left(FE_{t+1}\Big/\overline{CTE}\right)^{P_4-1}\right)FE_{t+1}\right)\right\}$$

$$HH=\left\{L_0\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)^{\varepsilon_1} A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\gamma\varepsilon_1 FE_{t+1}^{\rho-1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho-1}-L_0\frac{\vartheta\varepsilon_1}{\varphi}\frac{FE_{t+1}}{\varphi}^{\vartheta-1}\left(1-\frac{FE_{t+1}}{\varphi}^{\vartheta}\right)^{\varepsilon_1-1} A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}\left((AC_{t+1}CE)^{\rho}+FE_{t+1}^{\rho}\right)^{\gamma\varepsilon_1/\rho}\right\}$$

And the above equation, when there is no fossil fuel energy left to use, will be:

$$\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}\{A_{t+1}K_{t+1}^{\alpha}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\gamma CE(AC_{t+1}CE)^{\gamma-1}\}+$$

$$\frac{\beta\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}}{\omega AC_0AC_{t+1}^{\theta}(l_{TL}L_{t+1})^{\omega}TY_{t+1}^{\omega-1}}\left\{\theta AC_0AC_{t+1}^{\theta-1}(l_{TL}L_{t+1}TY_{t+1})^{\omega}\right\}+$$

$$\frac{\beta\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}-\beta^2\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}}(\alpha\left(A_{t+1}K_{t+1}^{\alpha-1}(l_{PL}L_{t+1})^{1-\alpha-\gamma}\right)(AC_{t+1}CE)^{\gamma}+1-\delta)}{(\alpha\varepsilon_1-\varepsilon_2)L_0A_{t+1}^{\varepsilon_1}K_{t+1}^{\alpha\varepsilon_1-\varepsilon_2-1}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_{t+1}^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}(AC_{t+1}CE)^{\gamma\varepsilon_1}}*$$

$$(\gamma\varepsilon_1L_0A_t^{\varepsilon_1}K_t^{\alpha\varepsilon_1-\varepsilon_2}l_{PL}^{\varepsilon_1-\alpha\varepsilon_1-\varepsilon_1\gamma}L_t^{\varepsilon_2-\alpha\varepsilon_1-\gamma\varepsilon_1}CE^{\gamma\varepsilon_1}AC_t^{\gamma\varepsilon_1-1})=\frac{\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}}{\omega AC_0AC_t^{\theta}(l_{TL}L_t)^{\omega}TY_t^{\omega-1}}\qquad\text{(C29)}$$

Solving the market-based F.O.C

Solving the first-order conditions for households, we get:

$$\{c_t\}:\ \beta^t\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}=\lambda_{1t}\qquad\text{(C30)}$$

$$\{K_{t+1}\}:\ \lambda_{1t}=(1+r_{t+1})\lambda_{1t+1}\qquad\text{(C31)}$$

$$\{L_{t+1}\}:\ \beta^{t+1}\frac{C_{t+1}^{1-\sigma}}{L_{t+1}^{2-\sigma}}=\lambda_{1t+1}w_{t+1}-\lambda_{2t}+\lambda_{2t+1}(1+\bar{L})$$

And when the population grows endogenously, we have the below F.O.C:

$$\{K_{t+1}\}:\ \lambda_{1t}=(1+r_{t+1})\lambda_{1t+1}-\lambda_{2t+1}\varepsilon_2L_0L_{t+1}^{\varepsilon_2-\varepsilon_1}Y_{t+1}^{\varepsilon_1}K_{t+1}^{-\varepsilon_2-1}\qquad\text{(C32)}$$

$$\{L_{t+1}\}:\ \beta^{t+1}\frac{C_{t+1}^{1-\sigma}}{L_{t+1}^{2-\sigma}}=\lambda_{1t+1}w_{t+1}-\lambda_{2t}+\lambda_{2t+1}(1+L_0(\varepsilon_2-\varepsilon_1)Y_{t+1}^{\varepsilon_1}K_{t+1}^{-\varepsilon_2}L_{t+1}^{\varepsilon_2-\varepsilon_1-1})\qquad\text{(C33)}$$

Updating and substituting Equations C30 in C31, C32, and C33 we derive the Euler equations for households for both cases:

$$\frac{C_t^{-\sigma}}{L_t^{1-\sigma}} = \beta(1 + r_{t+1})\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}} \qquad \text{(Population is exogenous)} \qquad \text{(C34)}$$

$$\beta^2 \frac{C_{t+1}^{1-\sigma}}{L_{t+1}^{2-\sigma}} = \beta^2 \frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}} w_{t+1} - \frac{\left[(1+r_t)\beta\frac{C_t^{-\sigma}}{L_t^{1-\sigma}} - \frac{C_{t-1}^{-\sigma}}{L_{t-1}^{1-\sigma}}\right]}{\left[\varepsilon_2 L_0 L_t^{\varepsilon_2-\varepsilon_1} Y_t^{\varepsilon_1} K_t^{-\varepsilon_2-1}\right]} + \frac{\left[(1+r_{t+1})\beta^2\frac{C_{t+1}^{-\sigma}}{L_{t+1}^{1-\sigma}} - \beta\frac{C_t^{-\sigma}}{L_t^{1-\sigma}}\right]}{\left[\varepsilon_2 L_0 L_{t+1}^{\varepsilon_2-\varepsilon_1} Y_{t+1}^{\varepsilon_1} K_{t+1}^{-\varepsilon_2-1}\right]}\left(1 + L_0(\varepsilon_2 - \varepsilon_1) Y_{t+1}^{\varepsilon_1} K_{t+1}^{-\varepsilon_2} L_{t+1}^{\varepsilon_2-\varepsilon_1-1}\right) \qquad \text{(Population is endogenous)} \qquad \text{(C35)}$$

Solving the first-order conditions for the final good market, we have:

$$\{KY_t\}: \alpha EDA_t KY_t^{\alpha-1} PL_t^{1-\alpha-\gamma}\left(CE_t^{\rho} + FE_t^{\rho}\right)^{\gamma/\rho} = r_t + \delta \qquad \text{(C36)}$$

$$\{PL_t\}: (1-\alpha-\gamma) EDA_t KY_t^{\alpha} PL_t^{-\alpha-\gamma}(CE_t^{\rho} + FE_t^{\rho})^{\gamma/\rho} = w_t \qquad \text{(C37)}$$

$$\{FE_t\}: \gamma EDA_t KY_t^{\alpha} PL_t^{1-\alpha-\gamma} FE_t^{\rho-1}\left(CE_t^{\rho} + FE_t^{\rho}\right)^{\gamma/\rho-1} = P_{FEt} \qquad \text{(C38)}$$

$$\{CE_t\}: \gamma EDA_t KY_t^{\alpha} PL_t^{1-\alpha-\gamma} CE_t^{\rho-1}(CE_t^{\rho} + FE_t^{\rho})^{\gamma/\rho-1} = P_{CEt} \qquad \text{(C39)}$$

In the end, the F.O.C.s for the energy sector are:

$$\{FE_t\}: P_0 + P_1\left(\sum_{i=1}^{t} FE_i \Big/ \overline{FE}\right)^{P_2} + P_3\left(FE_t \Big/ \overline{CTE}\right)^{P_4} + \left(\frac{P_1 P_2}{\overline{FE}}\left(\sum_{i=1}^{t} FE_i \Big/ \overline{FE}\right)^{P_2-1} + \frac{P_3 P_4}{\overline{CTE}}\left(FE_t \Big/ \overline{CTE}\right)^{P_4-1}\right) FE_t = P_{FEt} \qquad \text{(C40)}$$

$$\{TL_t\}: \lambda_t \omega AC_0 AC_t^{\theta} TY_t (TL_t TY_t)^{\omega-1} = \beta^t w_t \qquad \text{(C41)}$$

$$\{TY_t\}: \lambda_t \omega AC_0 AC_t^{\theta} TL_t (TL_t TY_t)^{\omega-1} = \beta^t r_t \tag{C42}$$

$$\{AC_{t+1}\}: \lambda_t - \lambda_{t+1} AC_0 AC_t^{\theta} (TL_t TY_t)^{\omega} = \beta^{t+1} CE * P_{CEt+1} \tag{C43}$$

Combining Equations C41 and C42, we get:

$$TY_t = \frac{w_t}{r_t} TL_t \tag{C44}$$

Updating and substituting Equation C44 into C43, we get another Euler equation for the Energy sector:

$$\frac{w_t}{\omega AC_0 AC_t^{\theta} TY_t (TL_t TY_t)^{\omega-1}} - \beta CE * P_{CEt+1} = \frac{\beta w_{t+1}}{\omega AC_{t+1}^{\theta} TY_{t+1} (TL_{t+1} TY_{t+1})^{\omega-1}} AC_t^{\theta} (TL_t TY_t)^{\omega} \tag{C45}$$

Using Equations C38 and C40, we derive the price and the amount of fossil fuel energy.

Price of fossil fuel energy

In this setup for simplicity, a social planner needs to provide non-renewable energy (while she owns it). Thus she needs to spend some of her resources to extract it. In the market-based approach, the energy sector (as a monopoly) owns the resources but still needs to pay the extraction costs. This cost is similar in both models (social planner and market-based). However, unlike Stiglitz assumption in which cost of extraction is decreasing over time, in this model, it is increasing over time since it would be harder to extract the fossil fuel in the bottom of a reservoir (and when there is less energy reserve remains in the reservoir) compared to the full reservoir. Another distinction of this model versus Stiglitz (or in general Hotelling setup) is that the objective in those models is understanding a social planner should utilize the exhaustible resources. In the current setup, the purpose is how social planner should maximize household utility, which is the consumption per capita. And consumption itself is a function of different investments. In the end, it is noteworthy that if there is a strong and positive correlation between marginal cost and the price of fossil fuel, then that suggests the price of price fossil fuel has been increasing during the past decades while at the same time energy utilization has been increasing as well.

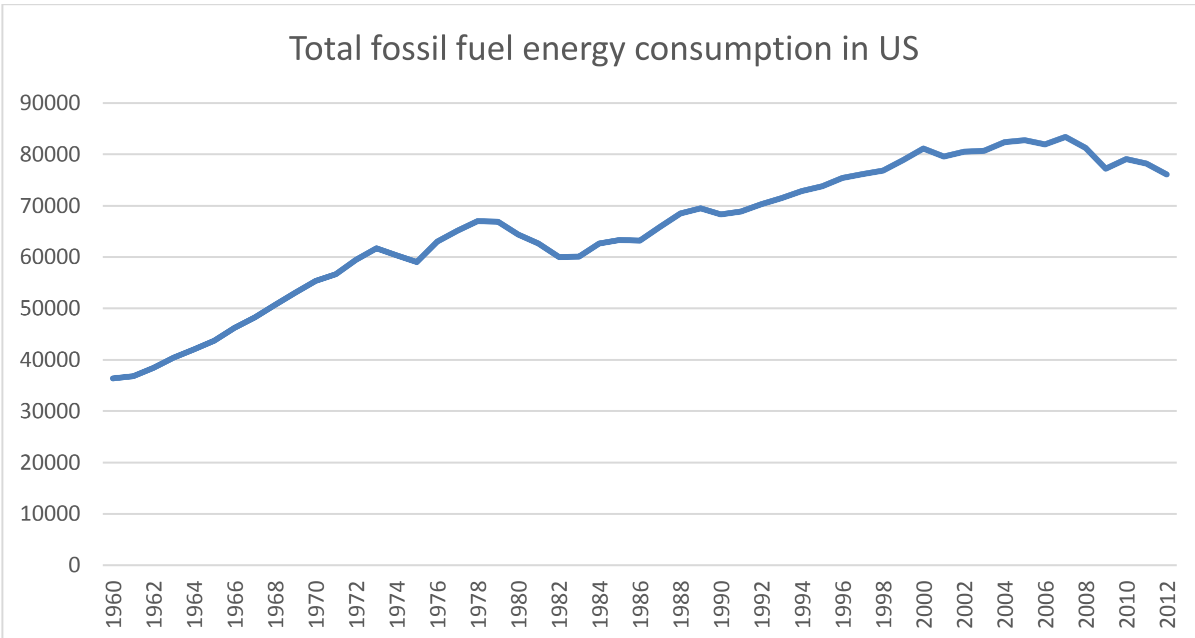


Figure 6: Total fossil fuel consumption in the U.S. from 1960 – 2012. As it is shown, the rate of consumption/production has been increasing while the price of providing it has also been growing.

Changing the capital share

In this section, I want to investigate two simple cases as a sensitivity analysis. First, the capital changes from 0.27 to 0.21. Second, an extra element would be added to the income allocation equation (Equation 3) to absorb the gap between the perfect income allocation of the model and the imperfect allocation of the real world (such as retirement, labor force participation, which is not 100% and so on). Therefore, instead of Equation 3, we will have:

$$Y_t = C_t + K_{t+1} - (1-\delta)K_t + P_{FEt}FE_t + TY_t + Mis_t \quad \text{(E1)}$$

The results—for the social planner approach when the population grows endogenously—are depicted in Figure 7. We can see that the economic growth is lower when there is a misallocation in income, and population tends to grow even faster. However, population growth is slower when capital share decreases ad labor share increases.

Figure 7 shows population growth and economic growth for three different cases. The blue lines show the base scenario when there is no misallocation of resources and the capital share is 0.27. Red lines show the case in which labor share increases by 6 percent. The yellow lines show that there exist 25% misallocation of the income. The social planner solution has been applied for all models.

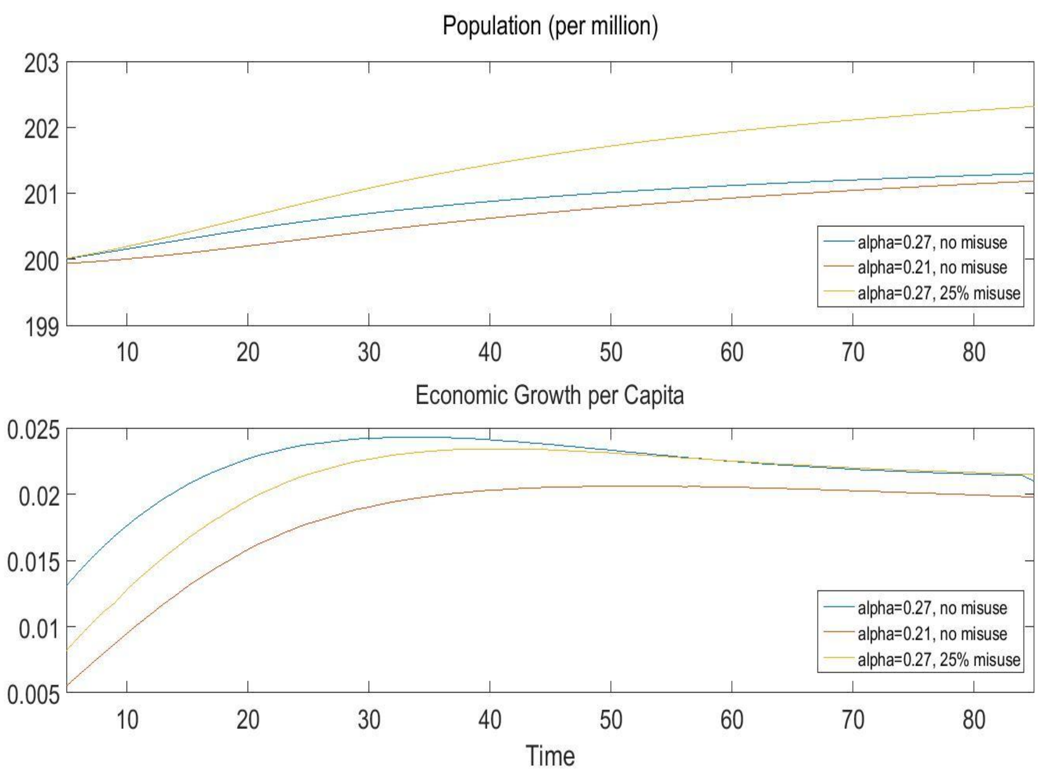


Figure 7: Population growth and economic growth for three different scenarios.

Altering the population growth

One would argue that the U.S. population grows around one percent, whereas, in the proposed model it converges to zero. Because of this, I have used different parameterization for Equation 15 ($L_{t+1} = L_t + L_0({}^{Y_t}/_{L_t})^{\varepsilon_1}({}^{L_t}/_{K_t})^{\varepsilon_2}$), to see if one percent growth rate in population is achievable using the current setup. As it is shown in Figure 7, a population can grow faster in the observed period's early stages; however, it tends to drop towards end. While the proposed model is well-fitted in Japan and Western European countries, we need to change the value of the parameters in Equation 15 ($\varepsilon_1 = 1.72 \rightarrow 1.8$, $\varepsilon_2 = 2.18 \rightarrow 2.1$ and $L_0 = 2.35 \rightarrow 12.35$) to capture the growth rate in population for US.

For the case of the US, I can think of a plausible argument. If we deduct US immigration rate (including immigrants' descendants, although they might be the U.S.-born), the population growth would be much lower than the current rate. Although the counter argument would be that they still participate in the economy, however, they are not born in that economy but are brought in. The proposed model shows a high growth rate in early stages, so we can think about the entrance of immigrants with the high rate of population which, tends to converge to its steady state.

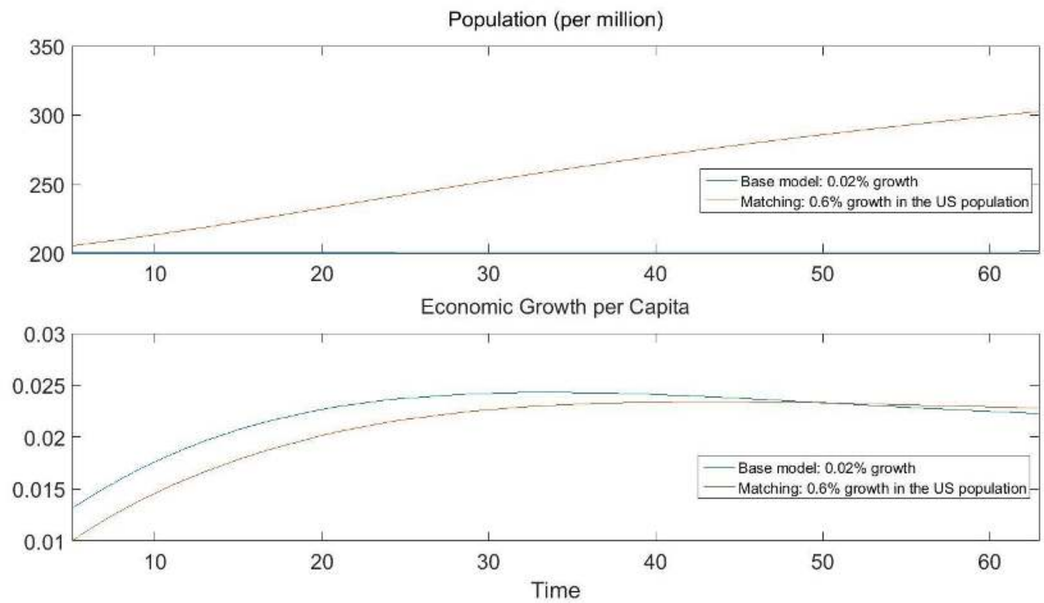


Figure 8: Economic growth for two different scenarios of population growth.

Figure 8 shows population and economic growth for two different scenarios of population growth. The blue lines show the base model scenario in which population grows at 0.02 percent rate. The red lines match the U.S. population growth which is about 0.6 percent on average. The social planner solution has been applied for both models.

Assigning different utility function

In another attempt, instead of exogenously imposing a social cost of using the fossil fuel-based energy, we can tweak the individuals' utility function in such a way that they evaluate the air quality (the environment in general) as another good. Under these conditions, the utility maximization process is:

$$\text{Max}\, W = E_0 \sum_{t=0}^{T} \beta^t \frac{(c_t^{\mu} ED_t^{1-\mu})^{1-\sigma}}{1-\sigma} \qquad c_t = {C_t}/{L_t} \qquad \text{(G1\&G2)}$$

The only difference in the above household maximization setting, compared to the social planner approach, is the idea arising from Rosen (1974) in which individuals evaluate the air quality as a commodity and add it to their consumption bundle accordingly. Since households would profit from firms, ultimately, air quality is endogenous within this setup. In the above setting, if individuals do not care for the environment, we can simply calibrate the value of μ to one. Thus, we get the same utility as we had before. Based on the degree of the individuals' awareness of the importance of the environment, this amount would be somewhere between zero and one. Updating Equations C34 and C35 by including the environmental degradation we have:

$$ED_t^{(1-\mu)(1-\sigma)} C_t^{\mu-\mu\sigma-1} L_t^{\mu\sigma-\mu} = \beta(1 + r_{t+1}) ED_{t+1}^{(1-\mu)(1-\sigma)} C_{t+1}^{\mu-\mu\sigma-1} L_{t+1}^{\mu\sigma-\mu} \tag{G3}$$

$$\beta^2 ED_t^{(1-\mu)(1-\sigma)} C_t^{\mu-\mu\sigma} L_t^{\mu\sigma-\mu-1} = \beta^2 ED_{t+1}^{(1-\mu)(1-\sigma)} C_{t+1}^{\mu-\mu\sigma-1} L_{t+1}^{\mu\sigma-\mu} w_{t+1} - \frac{\left[(1+r_t)\beta ED_t^{(1-\mu)(1-\sigma)} C_t^{\mu-\mu\sigma-1} L_t^{\mu\sigma-\mu} - ED_{t-1}^{(1-\mu)(1-\sigma)} C_{t-1}^{\mu-\mu\sigma-1} L_{t-1}^{\mu\sigma-\mu}\right]}{\left[\varepsilon_2 L_0 L_t^{\varepsilon_2-\varepsilon_1} Y_t^{\varepsilon_1} K_t^{-\varepsilon_2-1}\right]} + \frac{\left[(1+r_{t+1})\beta^2 ED_{t+1}^{(1-\mu)(1-\sigma)} C_{t+1}^{\mu-\mu\sigma-1} L_{t+1}^{\mu\sigma-\mu} - \beta ED_t^{(1-\mu)(1-\sigma)} C_t^{\mu-\mu\sigma-1} L_t^{\mu\sigma-\mu}\right]}{\left[\varepsilon_2 L_0 L_{t+1}^{\varepsilon_2-\varepsilon_1} Y_{t+1}^{\varepsilon_1} K_{t+1}^{-\varepsilon_2-1}\right]} \left(1 + L_0(\varepsilon_2 - \varepsilon_1) Y_{t+1}^{\varepsilon_1} K_{t+1}^{-\varepsilon_2} L_{t+1}^{\varepsilon_2-\varepsilon_1-1}\right) \tag{G4}$$

The results are summarized in Figure 9. Households tend to consume less in the environmental friendly model compared to the others. However, it does not have any impact on fossil fuel production pattern.

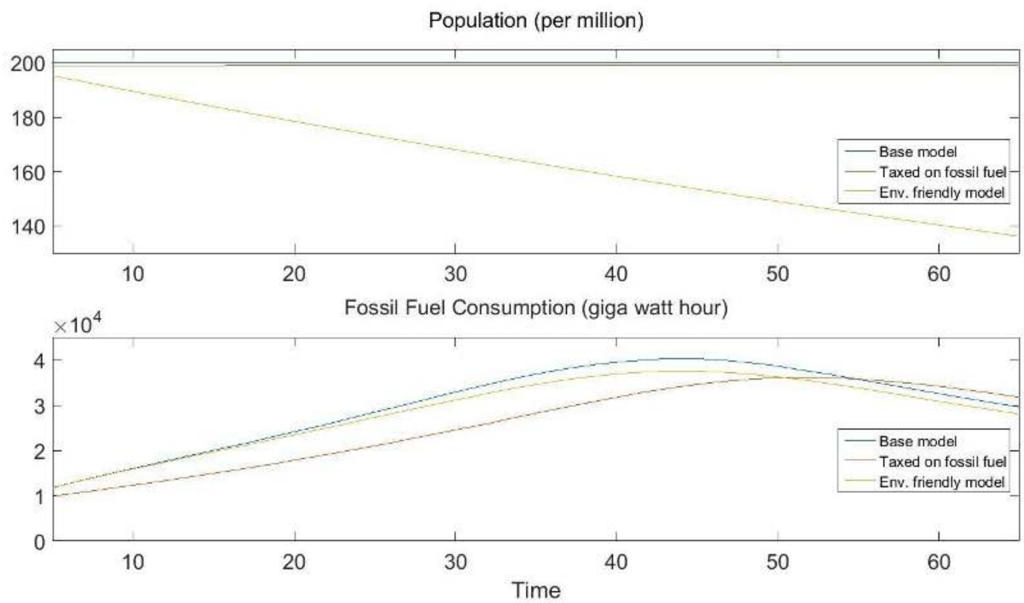


Figure 9: Population growth and fossil fuel utilization for the environmental friendly model.

Figure 9 shows population growth and fossil fuel utilization for three different scenarios. The blue lines are for the base model. The red lines show the elements when there is an element of carbon tax. And the yellow lines show when individuals evaluate environment as another good in their utility maximization. All models are decentralized.

Appendix to Chapter II

Table 7: The summary statistics of the respondents

Item	# Observation	Description		Control	Treat-1	Treat-2	Treat-3
Occupation	665	Faculty	26.53%	29.93%	30.38%	35.51%	30.14%
		Staff	43.54%	43.54%	41.77%	31.31%	43.84%
		Student	29.93%	26.53%	27.85%	33.18%	26.03%
Gender	664	Female	61.75%	60.54%	64.97%	58.41%	64.38%
		Male	38.25%	39.46%	35.03%	41.59%	35.62%
Education	665	High school	8.43%	8.16%	5.06%	11.68%	7.53%
		Some college	15.81%	13.61%	16.46%	16.82%	15.75%
		College degree	23.80%	25.85%	24.05%	23.83%	21.92%
		Post-grad	51.96%	52.38%	54.43%	47.66%	54.79%
Birth place	665	US born	85.86%	85.03%	81.65%	87.38%	89.04%
		Foreign born	14.14%	14.97%	18.35%	12.62%	10.96%
Marital status	662	Divorced	10.12%	8.84%	12.10%	8.92%	11.03%
		Married	46.37%	46.94%	47.13%	46.01%	45.52%
		Never married	40.79%	42.86%	36.94	41.31%	42.07%
		Separated	1.21%	0.00%	1.27%	2.35%	0.69%
		Widowed	1.51%	1.36%	2.55%	1.41%	0.69%
# Kids	664	None	54.22%	53.74%	50.96%	53.27%	59.59%
		1 or 2	33.88%	31.29%	36.94%	35.98%	30.14%
		3 or more	11.90%	14.97%	12.10%	10.75%	10.27%
Age	643	Mean	40.3	40.3	40.5	40.5	39.9
		Std. Deviation	14.7	14.7	14.2	14.9	14.9
		Median	40	39	40.5	42	39
		Min	18	18	18	18	18
		Max	75	75	73	75	75
Income	550	Mean	52,966	48,996	59,379	53,077	50,875
		Std. Deviation	43,817	30,900	59,425	39,727	40,723
		Min	0	0	0	0	0
		Max	500,000	150,000	500,000	180,000	240,000
Sign the petition	665	Yes	67.52%	62.59%	55.06%	77.10%	71.92%
		No	32.48%	37.41%	44.94%	22.90%	28.08%
		Number	665	147	158	214	146
If sign which tax	449	10% Carbon tax	72.61%	72.83%	72.41%	69.70%	77.14%
		1% sales tax	27.39%	27.17%	27.59%	30.30%	22.86%

Table 8: Probit analysis to determine any attribute impacts on the individuals' decisions

	(1) Sign the petition	(2) Sign the petition	(3) Sign the petition
Treatment 1	-0.194	-0.212	-0.297
	(0.14535)	(0.15090)	(0.16729)
Treatment 2	0.421**	0.426**	0.310
	(0.14183)	(0.14705)	(0.16332)
Treatment 3	0.260	0.229	0.0973
	(0.15265)	(0.15754)	(0.17395)
Age	-	-0.0132*	-0.00888
		(0.00522)	(0.00596)
Occupation	-	0.223*	0.263*
		(0.10813)	(0.11597)
Education	-	0.104	0.115
		(0.07470)	(0.08220)
Income	-	-	1.84e-08
			(0.00000)
Controls*	No	Yes	Yes
N	665	638	535

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
*Other controls are: gender, marital status, number of the kids, and birth place.

Table 9: Probit analysis to determine any attribute impacts on the individuals' tax plan (sales tax)

	(1) Sales Tax	(2) Sales Tax	(3) Sales Tax
Treatment 1	0.0124 (0.20050)	0.00368 (0.20703)	-0.00352 (0.22071)
Treatment 2	0.0919 (0.17352)	0.0726 (0.17783)	0.0227 (0.18958)
Treatment 3	-0.136 (0.19487)	-0.113 (0.19941)	-0.0713 (0.21196)
Age		-0.00118 (0.00666)	0.00102 (0.00741)
Occupation	-	0.000373 (0.13020)	-0.0312 (0.14122)
Education	-	-0.0456 (0.09680)	-0.0745 (0.10538)
Income	-	-	0.000000531 (0.00000)
Controls*	No	Yes	Yes
N	449	434	375

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
*Other controls are: gender, marital status, number of the kids, and birth place.

Table 10: Power analysis among different groups

ANALYSIS	TOTAL SAMPLE	ALPHA	POWER
C VS T1	1029	0.05	0.8
C VS T2	192	0.05	0.8
T1 VS T2	92	0.05	0.8

Survey

Participation in research is voluntary. You do not have to be in this study. If you decide to be in the study and change your mind, you have the right to drop out at any time. You may skip questions or stop participating at any time. Whatever you decide, you will not lose any benefits to which you are otherwise entitled.

If you are willing to volunteer for this research, please continue with the survey.

Personal Background Information

1. What is your gender (Female, male):

2. What is your age:

3. What is your occupation (Faculty, staff, student):

4. What is your yearly income:

5. What is the highest completed degree you have earned (High school grad, some college, college grad, postgrad degree):

6. Are you the US-born or Foreign-born:

7. What is your marital status (Married, never married, divorced, widowed or separated):

8. How many kids do you have (None, 1 or 2, 3 or more):

US Energy and Carbon emission information, and environmental issues

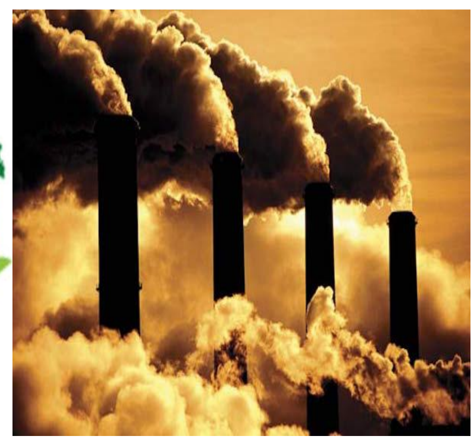
Now, we are going to give you some information on energy consumption in the United States:

Primary Energy Consumption in the US by Source and Sector in 2014

Table S.1: US Sources of Energy.

Source	**Petroleum**	**Natural gas**	**Coal**	**Renewable**	**Nuclear**
% of Total	**35.5%**	**28.0%**	**18.2%**	**9.8%**	**8.5%**
Use in	Transportation	Industrial &	Electrical	Electrical	Electrical

As it is shown in Table above, more than 80% of the US energy consumption supplies by fossil-based energy, which produces more than 15 billion metric tons of carbon dioxide. To give you an idea about the magnitude of this amount, the forests required to sequester the produced carbon every year in the US, is more than 15 times of the existing forests in the US!



Carbon emissions from coal are about 25 times more than solar PV to produce the same amount to generate electricity; and more than double about natural gas; and still around one-fifth of the total energy produces by coal because it is marginally cheaper and available, excluding the environmental damages it causes.

Below is the Energy Consumption Comparison between the three different treatment groups:

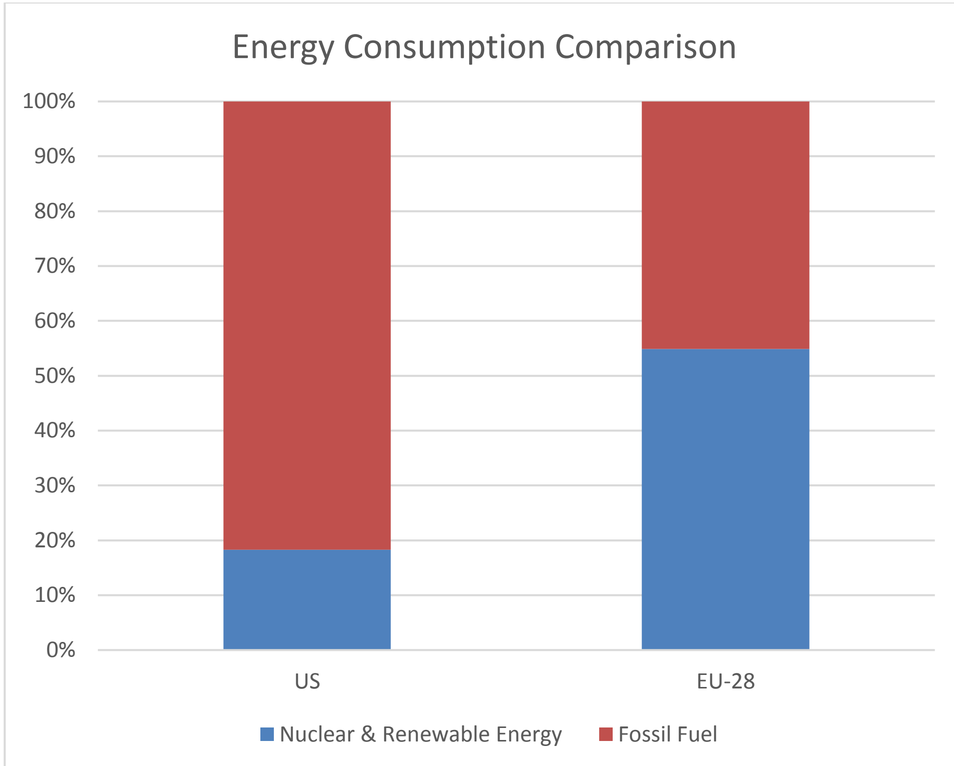
1- **US vs. EU:**

Table below shows energy-type use in the US and the European countries. We can see while less than 20% of the total energy production of the US is provided by renewable energy and nuclear power (we can call it clean energy); the European countries utilize more than 50% of their energy production from the clean energy.

Table S.2: US vs. EU Energy Use.

Countries	Renewable/Nuclear Energy	Fossil-based Energy (Oil/natural gas/coal)
US	18.3%	81.7%
EU-28	54.9%	45.1%

The below graphical bar shows the energy production ratio between clean energy and fossil fuel energy for the US and EU countries.



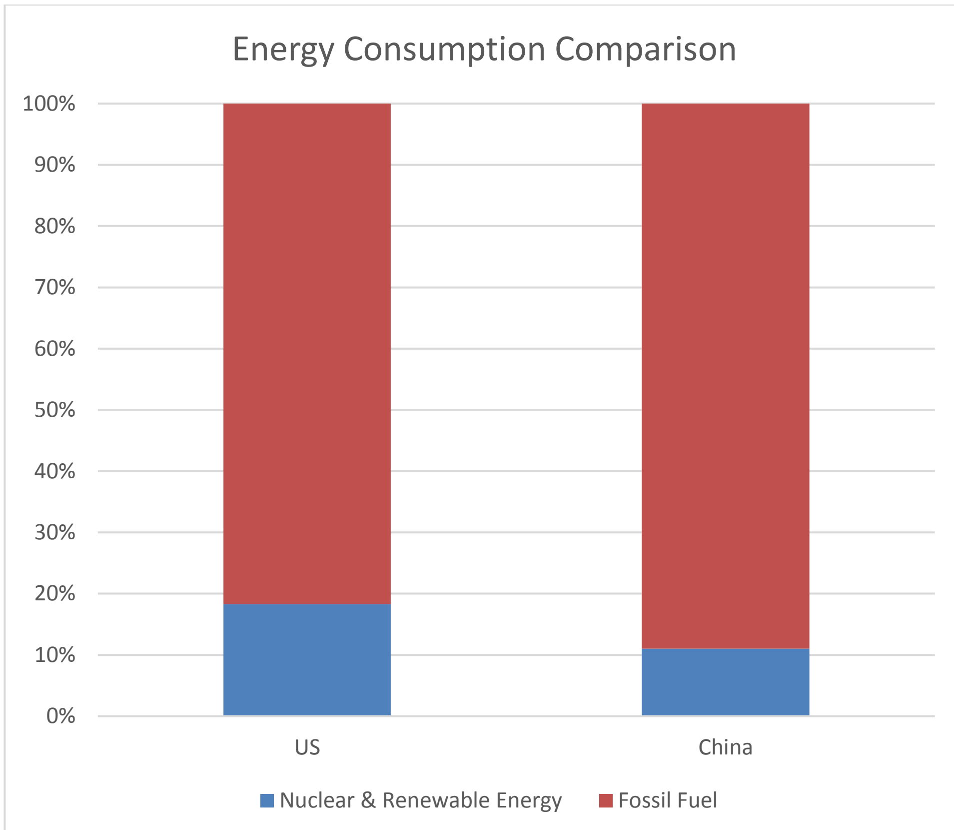
2- US vs. China:

Table below shows energy-type use in the US and China. We can see while less than 20% of the total energy production of the US is provided by renewable energy and nuclear power (we can call it clean energy); China even utilizes less than us; about 11% of their energy production comes from the clean energy.

Table S.3: US vs. China Energy Use.

Countries	Renewable/Nuclear Energy	Fossil-based Energy (Oil/natural gas/coal)
US	18.3%	81.7%
China	11.0%	89.0%

The below graphical bar shows the energy production ratio between clean energy and fossil fuel energy for the US and China.



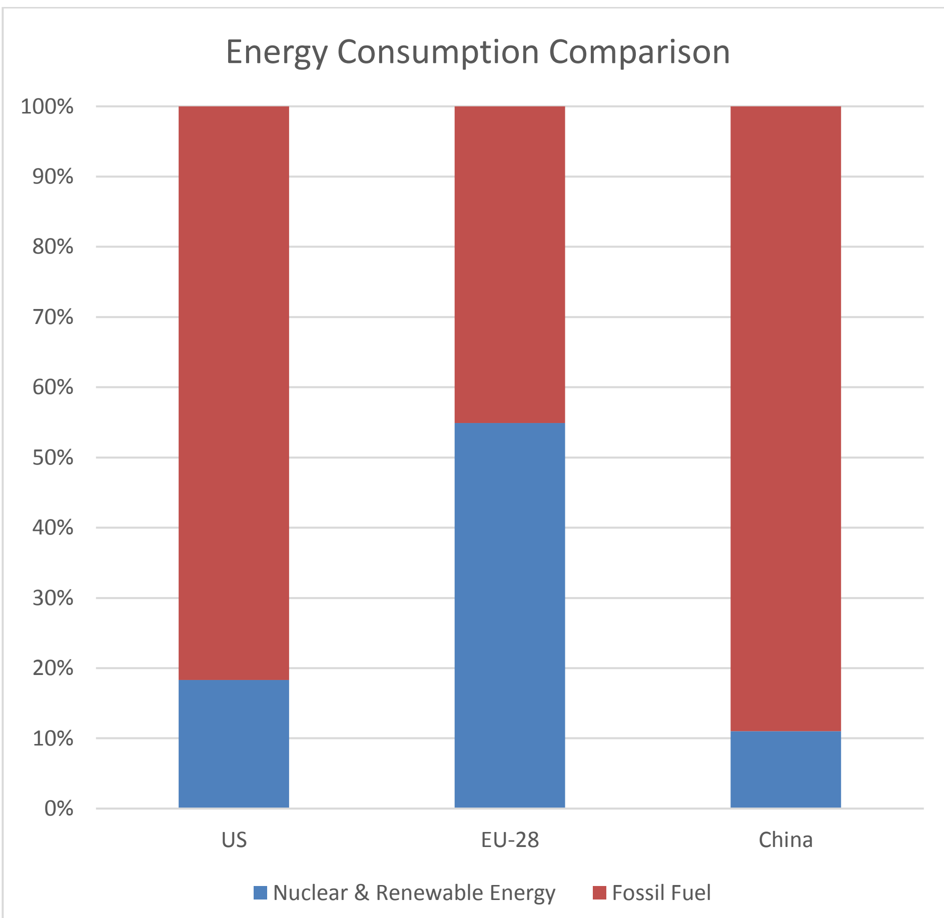
3- **US, EU, and China:**

Table below shows energy-type use in the US, the European countries, and China. We can see while less than 20% of the total energy production of the US is provided by renewable energy and nuclear power (we can call it clean energy). The European countries utilize more than 50% of their energy production from the clean energy; while this ratio is about 11% for China which is even less than The US.

Table S.4: US, EU and China Energy Use Comparison.

Countries	Renewable/Nuclear Energy	Fossil-based Energy (Oil/natural gas/coal)
US	18.3%	81.7%
EU-28	54.9%	45.1%
China	11.0%	89.0%

The below graphical bar shows the energy production ratio between clean energy and fossil fuel energy for the US, EU countries, and China.



Tax Reform Petition

As climate change becomes increasingly recognized as the key environmental issue of our times, there is an overwhelming scientific consensus that only a substantial reduction in greenhouse gas emissions can reduce the risks and impacts associated with climate change. To achieve meaningful reductions, we will need to change our energy use patterns. One of the more immediate but costly paths to accomplish this is to change energy-based resources. To do that, we want Governor Deal to consider the current tax reform petition to either

1. Impose ten percent carbon pollution tax on the fossil-based power plants and industries, and, with the generated income, subsidizes the renewable/nuclear energy users. A carbon tax is an extra fee for making users of fossil fuels pay for climate damage their fuel use imposes by releasing CO_2 into the air and for motivating switches to clean energy because it increases the cost of power production and incentivizes the producers to change the energy sources.

or

2. Increase one percent sales tax to subsidize renewable/nuclear energy users.

Will you sign the petition in either case (Yes/No)?

If your answer is yes, which of the Tax Reform do you prefer (1/2)?

Thank You!

Appendix to Chapter III

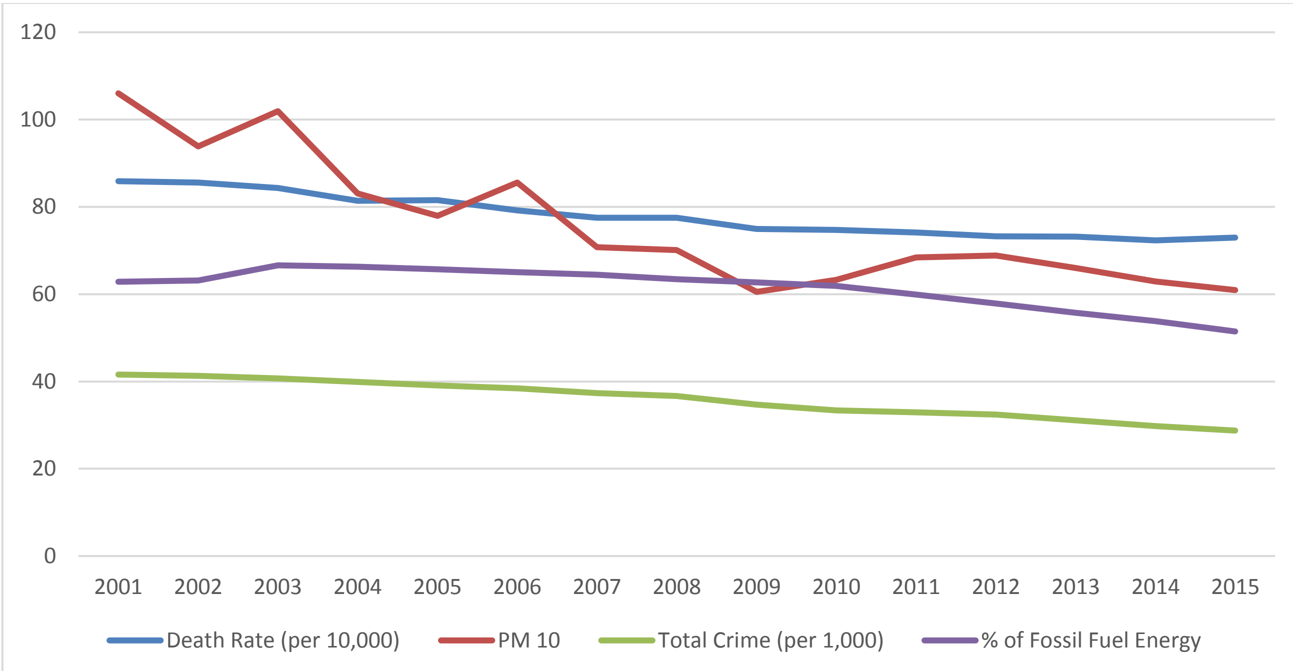


Figure 10: Percentage of Fossil fuel energy to total energy consumption, Air pollution (PM10), total crime rates, and death rate in the US from 2001 to 2015.

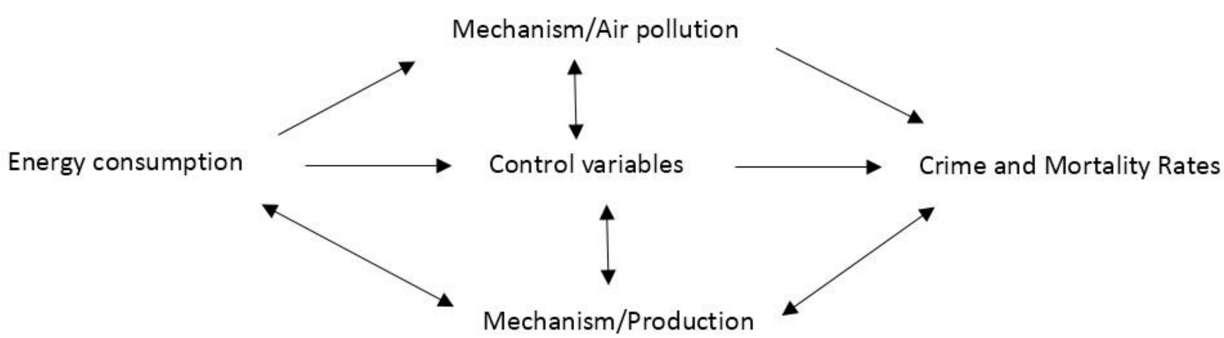


Figure 11: Illustrating the applied empirical model, and the channels of the impacts of each variable on crime and mortality rate

Table 11: Summary statistics of the main variables in the model (2001-2015, N=765).

State level data

Type	Variable	Unit	Mean	SD	Min	Max
Energy-Independent variables	Total Energy Consumption	Million BTU*	662968	633394	2812	5887435
	Fossil fuel-based Energy	Million BTU	402,188	335,504	2,812	2,039,651
	Coal-based Energy	Million BTU	53,680	49,714	0	229,746
	Clean Energy**	Million BTU	261,218	363,598	0	384,7784
Air Pollution and Income-Mechanisms	PM 10***	Microgram in cubic meter	8.493	11.918	0	68.798
	Average Income	US $	55,586	8,612	32,338	80,007
Controls	Population	No.	5,956,581	6,680,050	494,423	3.9e+07
	Police Officers	No.	19,030	22,951	1,238	123,506
	Unemployment Rate	Percentage	6.013	1.998	2.6	13.7
	House Price Index	Average price change	1.551	0.355	0.954	3.564
Social damages-dependent variables	Property Crime	No.	186,570	214,507	8,806	1,227,194
	Violent Crime	No.	25,892	33,789	493	212,855
	Mortality	No.	48,858	49,179	2,974	259,206
	Circulatory Death-cause	No.	16,361	17,331	797	93,373

* One unit of MMBTU equals 293 KWH

** It is combined of solar, hydro, wind, nuclear, biofuel energy

*** PM 10 uses as a proxy for air pollution in this study

Table 12: Basic results for the raw analysis.

	Energy: Total		Energy: Fossil fuel-based		Energy: Coal-based	
	(1)	(2)	(3)	(4)	(5)	(6)
	Violent Crime	Mortality	Violent Crime	Mortality	Violent Crime	Mortality
Total Energy	0.00169**	0.000676***				
	(0.001)	(0.000)				
Fossil fuel-based			0.00177*	0.000774**		
			(0.001)	(0.000)		
Coal-based					0.00287	0.00239**
					(0.002)	(0.001)
Pollution	1.043**	0.194	1.128***	0.226	1.165***	0.235
	(0.335)	(0.128)	(0.335)	(0.130)	(0.340)	(0.130)
Income	-0.000328	-0.000985**	-0.000303	-0.000983**	-0.000188	-0.000976**
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
Police officers	0.282**	-0.0291	0.319***	-0.0143	0.322***	-0.0113
	(0.095)	(0.040)	(0.095)	(0.039)	(0.096)	(0.040)
Housing price	16.93	-3.829	17.15	-3.662	14.80	-4.567
	(13.754)	(6.526)	(13.915)	(6.518)	(14.133)	(6.522)
Unemployment	-7.416*	-4.300***	-7.927**	-4.481***	-8.343**	-4.658***
	(3.005)	(1.191)	(3.044)	(1.184)	(3.073)	(1.183)
Year	-7.091***	0.596	-6.289***	0.894	-5.708***	1.126
	(1.176)	(0.625)	(1.104)	(0.606)	(1.095)	(0.594)
Fixed effects**	Yes	Yes	Yes	Yes	Yes	Yes
N	765	765	764	764	764	764
R^2	0.94	0.98	0.93	0.98	0.93	0.98

Standard errors in parentheses. The independent variables, respectively, are total energy consumption per capita*, fossil fuel energy consumption per capita, and coal consumption per capita in each state (which are depicted on the top rows of the Table); and the dependent variables are divided into two categories: violent crime rates and death rates.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

* Energy elements, number of the police officers, number of the crimes and deaths, are normalized per hundred thousand of residents

** State and year fixed effects

Table 13: Basic results for the mechanism approach (air pollution is the mechanism, dependent variable is the violent crime)*.

	Energy: Fossil fuel-based			Energy: Coal-based		
	(1) Violent Crime	(2) Air Pollution	(3) Violent Crime	(4) Violent Crime	(5) Air Pollution	(6) Violent Crime
Fossil fuel-based	0.00191*	0.000123*	0.00177*			
	(0.001)	(0.000)	(0.001)			
Coal-based				0.00356	0.000592	0.00287
				(0.002)	(0.000)	(0.002)
Air Pollution			1.128***			1.165***
			(0.335)			(0.340)
Controls**	Yes	Yes	Yes	Yes	Yes	Yes
N	764	764	764	764	764	764
R^2	0.93	0.84	0.93	0.93	0.84	0.93

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
* Variables have been normalized per 100,000 residents
** Housing prices, number of the police officers, rate of unemployment, income, year trend, state and year fixed effects

Table 14: Basic results for the mechanism approach (income is the mechanism, dependent variable is the violent crime)*.

	Energy: Fossil fuel-based			Energy: Coal-based		
	(1)	(2)	(3)	(4)	(5)	(6)
	Violent Crime	Income	Violent Crime	Violent Crime	Income	Violent Crime
Fossil fuel-based	0.00175*	0.0785**	0.00177*			
	(0.001)	(0.028)	(0.001)			
Coal-based				0.00277	0.548***	0.00287
				(0.002)	(0.137)	(0.002)
Income			-0.000303			-0.000188
			(0.001)			(0.001)
Controls**	Yes	Yes	Yes	Yes	Yes	Yes
N	764	764	764	764	764	764
R^2	0.93	0.93	0.93	0.93	0.93	0.93

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
* Variables have been normalized per 100,000 residents
** Housing prices, number of the police officers, rate of unemployment, air pollution, year trend, state and year fixed effects

Table 15: Basic results for the mechanism approach (air pollution is the mechanism, dependent variable is the mortality rate)*.

	Energy: Fossil fuel-based			Energy: Coal-based		
	(1)	(2)	(3)	(4)	(5)	(6)
	Mortality	Air Pollution	Mortality	Mortality	Air Pollution	Mortality
Fossil fuel-based	0.000802**	0.000123*	0.000774**			
	(0.000)	(0.000)	(0.000)			
Coal-based				0.00253**	0.000592	0.00239**
				(0.001)	(0.000)	(0.001)
Air Pollution			0.226			0.235
			(0.130)			(0.130)
Controls**	Yes	Yes	Yes	Yes	Yes	Yes
N	764	764	764	764	764	764
R^2	0.98	0.84	0.98	0.98	0.84	0.98

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

* Variables have been normalized per 100,000 residents

** Housing prices, number of the police officers, rate of unemployment, income, year trend, state and year fixed effects

Table 16: Basic results for the mechanism approach (income is the mechanism, dependent variable is the mortality rate)*.

	Energy: Fossil fuel-based			Energy: Coal-based		
	(1) Mortality	(2) Income	(3) Mortality	(4) Mortality	(5) Income	(6) Mortality
Fossil fuel-based	0.000697**	0.0785**	0.000774**			
	(0.000)	(0.028)	(0.000)			
Coal-based				0.00186*	0.548***	0.00239**
				(0.001)	(0.137)	(0.001)
Income			-0.000983**			-0.000976**
			(0.000)			(0.000)
Controls**	Yes	Yes	Yes	Yes	Yes	Yes
N	764	764	764	764	764	764
R^2	0.98	0.93	0.98	0.98	0.93	0.98

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

* Variables have been normalized per 100,000 residents

** Housing prices, number of the police officers, rate of unemployment, air pollution, year trend, state and year fixed effects

Table 17: IV approach using political affiliation to predict the energy variables*.

	Energy: Fossil fuel-based		Energy: Coal-based	
	(1) Violent Crime	(2) Mortality	(3) Violent Crime	(4) Mortality
Fossil fuel-	-0.0157	-0.0149		
	(0.027)	(0.018)		
Coal-based			-0.0386	-0.0366
			(0.050)	(0.027)
Air Pollution	1.672	0.714	1.430**	0.484*
	(0.989)	(0.587)	(0.507)	(0.207)
Income	0.00191	0.000995	0.00139	0.000507
	(0.004)	(0.002)	(0.002)	(0.001)
Controls**	Yes	Yes	Yes	Yes
N	764	764	764	764
R^2	0.83	0.88	0.91	0.96

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

* Variables have been normalized per 100,000 residents

** Housing prices, number of the police officers, rate of unemployment, year trend, state and year fixed effects

Table 18: Altonji Table, while the dependent variable is violent crime rate.

	Energy: Fossil Fuel-based		Energy: Coal-based	
Energy	Uncontrolled	Controlled*	Uncontrolled	Controlled*
Coefficient	-0.00114	0.00177	-0.02674	0.00287
R-Squared	0.005	0.934	0.066	0.933
Delta	-2.58065		-0.27467	

* In this analysis, income and pollution are also have been considered as control variables (beside housing prices, rate of unemployment, number of the police officers, year trend, State and year fixed effects).

Table 19: Altonji Table, while the dependent variable is mortality rate.

	Energy: Fossil Fuel-based		Energy: Coal-based	
Energy	Uncontrolled	Controlled*	Uncontrolled	Controlled*
Coefficient	-0.00085	0.00077	0.02422	0.00239
R-Squared	0.004	0.983	0.068	0.983
Delta	-6.71506		1.17395	

* In this analysis, income and pollution are also have been considered as control variables (beside housing prices, rate of unemployment, number of the police officers, year trend, State and year fixed effects).

Table 20: Placebo test using the elements similar to the dependent variable, while the dependent variables are violent crime and property crime rates*.

	Energy: Fossil fuel-based		Energy: Coal-based	
	(1) Violent Crime	(2) Property Crime	(3) Violent Crime	(4) Property Crime
Fossil fuel-	0.00177*	0.00512**		
	(0.0008)	(0.0017)		
Coal-based			0.00287	0.00789
			(0.0018)	(0.0102)
Air Pollution	1.128***	-2.319	1.165***	-2.210
	(0.3345)	(1.4125)	(0.3396)	(1.4248)
Income	-0.000303	-0.00432	-0.000188	-0.00397
	(0.0007)	(0.0035)	(0.0007)	(0.0036)
Controls**	Yes	Yes	Yes	Yes
Fixed	Yes	Yes	Yes	Yes
N	764	764	764	764
R^2	0.934	0.935	0.933	0.935

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
* Variables have been normalized per 100,000 residents
** Housing prices, number of the police officers, rate of unemployment, and year trend
*** State and year fixed effects

Table 21: Placebo test using the elements similar to the dependent variable, while the dependent variables are circulatory cause and external causes of death*.

	Energy: Fossil fuel-based		Energy: Coal-based	
	(1) Circulatory	(2) External	(3) Circulatory	(4) External
Fossil fuel-based	0.000323	0.000147***		
	(0.0002)	(0.0000)		
Coal-based			0.00111*	0.000486*
			(0.0004)	(0.0002)
Air Pollution	0.289***	-0.0886**	0.292***	-0.0871**
	(0.0634)	(0.0300)	(0.0635)	(0.0304)
Income	-0.000513**	-0.0000110	-0.000514**	-0.0000108
	(0.0002)	(0.0001)	(0.0002)	(0.0001)
Controls**	Yes	Yes	Yes	Yes
Fixed effects***	Yes	Yes	Yes	Yes
N	764	764	764	764
R^2	0.979	0.939	0.979	0.938

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
* Variables have been normalized per 100,000 residents
** Housing prices, number of the police officers, rate of unemployment, and year trend
*** State and year fixed effects

Table 22: Test for the endogeneity of the error terms for the violent crime and mortality rate using the Imai et al. (2010) sensitivity method.

	Violent Crime		Mortality	
	Mechanism: ε_{3j}	Mechanism: ε_{3j}	Mechanism: ε_{3j}	Mechanism: ε_{3j}
ε_{2i}	0.187	0.187	0.187	0.187
	(0.3948)	(0.3948)	(0.3948)	(0.3948)
N	764	764	764	764
R^2	0.953	0.953	0.953	0.953

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 23: Testing for income effect to verify whether the high income states are different in environmental policy and energy subsidy compared to the lower income states*.

	High Income States**		Low Income States		All the States	
	(1) Violent Crime	(2) Mortality	(3) Violent Crime	(4) Mortality	(5) Violent Crime	(6) Mortality
Coal-based Energy	0.00242	0.00124	0.00917	0.00955*	0.00287	0.00239**
	(0.0017)	(0.0010)	(0.0131)	(0.0047)	(0.0018)	(0.0009)
Air Pollution	0.868*	0.531***	2.432***	0.236	1.165***	0.235
	(0.3407)	(0.1428)	(0.6478)	(0.2373)	(0.3396)	(0.1304)
Income	-0.0000424	-0.000181	-0.000467	-0.000921	-0.000188	-0.000976**
	(0.0009)	(0.0004)	(0.0013)	(0.0006)	(0.0007)	(0.0003)
Controls***	Yes	Yes	Yes	Yes	Yes	Yes
N	390	390	374	374	764	764
R^2	0.945	0.987	0.930	0.966	0.933	0.983

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
* Variables have been normalized per 100,000 residents
** High income States are the ones who they income in 2015 is above the average income in this dataset ($57000)
*** Housing prices, number of the police officers, rate of unemployment, year trend, State and year fixed effects

Clean energy vs. coal-based energy

In the last attempt, I compare the results of the mechanism approach between clean energy and coal-based energy. Tables 14 and 15 show the results when violent crime rates is the dependent variable. Air pollution is the mechanism in the first table, and income is the mechanism in the second. Similarly, Tables 16 and 17 depict the result while the dependent variable is mortality rates. Setting the violent crime rates as our dependent variable, we can see that when using clean energy, the mechanism effect of air pollution is 4.3E-4; when switching clean energy to coal-based energy, this effect is bigger and equal to 6.9E-4. On the other hand, the income effect is smaller in clean energy versus coal-based energy (-4.5E-6 versus -1.04E-4). The similar scenario is valid when we switch the dependent variable to mortality rates. Utilizing clean energy, the mechanism effect of air pollution is 7.97E-5, while switching clean energy to coal-based energy, this effect is bigger and equal to 1.4E-4. At the same time, the income effect is smaller in clean energy versus coal-based energy (-2.7E-5 versus -5.4E-4). I can conclude that switching coal-based energy to clean energy decreases air pollution and income at the same time. However, the magnitude of the effect of this change is higher via income channel compared to air pollution. While air pollution impact decreases by around forty percent for violent crime rates and mortality rates, income effect diminished by 95 percent. This computation shows that moving away from coal-based energy and utilize clean energy to generate power, almost neutralizes the income mechanism while decreasing air pollution significantly; accordingly, social damages that arise from energy utilization drops as well as environmental externalities.

Table 24: Basic results for the mechanism approach (air pollution is the mechanism). The independent variables, respectively, are clean energy consumption and coal-based consumption, and the dependent is violent crime rates*.

	Energy: Clean			Energy: Coal-based		
	(1) Violent Crime	(2) Air Pollution	(3) Violent Crime	(4) Violent Crime	(5) Air Pollution	(6) Violent Crime
Energy	0.00392***	0.000433**	0.00349***	0.00356	0.000592	0.00287
	(0.001)	(0.000)	(0.001)	(0.002)	(0.000)	(0.002)
Air Pollution			1.000**			1.165***
			(0.343)			(0.340)
Controls**	Yes	Yes	Yes	Yes	Yes	Yes
N	765	765	765	764	764	764
R^2	0.93	0.84	0.94	0.93	0.84	0.93

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
* Variables have been normalized per 100,000 residents
** Housing prices, number of the police officers, rate of unemployment, income, year trend, state and year fixed effects

Table 25: Basic results for the mechanism approach (income is the mechanism). The independent variables, respectively, are clean energy consumption and coal-based consumption, and the dependent is violent crime rates*.

	Energy: Clean			Energy: Coal-based		
	(1)	(2)	(3)	(4)	(5)	(6)
	Violent Crime	Income	Violent Crime	Violent Crime	Income	Violent Crime
Energy	0.00348***	0.0294	0.00349***	0.00277	0.548***	0.00287
	(0.001)	(0.053)	(0.001)	(0.002)	(0.137)	(0.002)
Income			-0.000154			-0.000188
			(0.001)			(0.001)
Controls**	Yes	Yes	Yes	Yes	Yes	Yes
N	765	765	765	764	764	764
R^2	0.94	0.93	0.94	0.93	0.93	0.93

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
* Variables have been normalized per 100,000 residents
** Housing prices, number of the police officers, rate of unemployment, air pollution, year trend, state and year fixed effects

Table 26: Basic results for the mechanism approach (air pollution is the mechanism). The independent variables, respectively, are clean energy consumption and coal-based consumption, and the dependent is mortality rates*.

	Energy: Clean			Energy: Coal-based		
	(1) Mortality	(2) Air	(3) Mortality	(4) Mortality	(5) Air	(6) Mortality
Energy	0.00134***	0.000433**	0.00126***	0.00253**	0.000592	0.00239**
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)
Air			0.184			0.235
			(0.127)			(0.130)
Controls*	Yes	Yes	Yes	Yes	Yes	Yes
N	765	765	765	764	764	764
R^2	0.98	0.84	0.98	0.98	0.84	0.98

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

* Variables have been normalized per 100,000 residents

** Housing prices, number of the police officers, rate of unemployment, income, year trend, state and year fixed effects

Table 27: Basic results for the mechanism approach (income is the mechanism). The independent variables, respectively, are clean energy consumption and coal-based consumption, and the dependent is mortality rates*.

	Energy: Clean			Energy: Coal-based		
	(1)	(2)	(3)	(4)	(5)	(6)
	Mortality	Income	Mortality	Mortality	Income	Mortality
Energy	0.00123***	0.0294	0.00126***	0.00186*	0.548***	0.00239**
	(0.000)	(0.053)	(0.000)	(0.001)	(0.137)	(0.001)
Income			-0.000913**			-0.000976**
			(0.000)			(0.000)
Controls **	Yes	Yes	Yes	Yes	Yes	Yes
N	765	765	765	764	764	764
R^2	0.98	0.93	0.98	0.98	0.93	0.98

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
* Variables have been normalized per 100,000 residents
** Housing prices, number of the police officers, rate of unemployment, air pollution, year trend, state and year fixed effects

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Vita

Faraz Farhidi was born on March 29, 1983, in Tehran, Iran. He holds a Bachelor of Science in Marine Engineering from Amir Kabir University located Tehran, followed by a Master of Arts in Economics from University of Isfahan, in Iran. He attended University of Central Florida in Orlando Florida, to study a PhD in water resource engineering in 2012. However, he decided to pursue a career in Economics and enrolled in PhD in Economics at Georgia State University.

He was awarded a PhD in economics in 2018 from that very university. Upon graduation, he will start working as an assistant professor in David D. Reh School of Business at Clarkson University.

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During his graduate studies, Faraz published papers in the top energy journals such as *Renewable and Sustainable Energy Reviews* and *Energy Buildings*. He also presented his works on various Economics topics at prominent conference such as ASSA and IEEE.

In addition to his teaching and research activities, he served as president of the Graduate Student Association in the Economic department. Besides his achievements in academia, Faraz worked as an engineer and manager on construction sites for more than five years in various positions, starting from the very bottom as a beginner engineer in a technical office, and later being promoted to a site manager.