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Green taxes, R&D investments, and emission abatement

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ADB Working Paper Series

**GREEN TAXES, R&D INVESTMENTS,
AND EMISSION ABATEMENT**

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Abstract

This study explores how energy tax influences energy R&D investments, which further affect economic welfare, carbon emissions, and climate change under various emission abatement policies. Energy tax, as a market-based instrument, aims to adjust the energy R&D investments to the optimal level. The study considers two types of energy tax, the optimal energy tax and the Pigovian tax. The optimal energy tax contains the scarcity rent and the carbon tax, while the Pigovian tax only considers the carbon tax. Setting the energy tax equal to the Pigovian tax appears to be insufficient, leading to sub-optimal outcomes. The impact is more significant before the energy use transits from fossil fuels to backstop technology, while the impact is moderate after the backstop technology fully replaces fossil fuels. The study shows that the sub-optimal outcomes are worse with a more restrictive abatement policy, while they are moderate under a less stringent abatement policy.

Keywords: optimal energy tax, Pigovian tax, scarcity rent, carbon tax, energy substitution, backstop technology, benefit–cost analysis

JEL Classifications: Q52, Q55, Q58

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1. INTRODUCTION

Global warming receives considerable attention due to its wide negative effects ranging from rising sea levels and regional changes in precipitation to more frequent extreme weather events, such as heatwaves. Mitigation efforts aim to reduce the emission of greenhouse gases (GHGs), such as carbon dioxide. When dealing with the emission abatement policy, policy makers have to make a long-term decision as carbon dioxide, once emitted, stays in the atmosphere for more than 50 years. The emission abatement policy also plays a role in inducing a technological change in energy use through the channel of R&D investments. Popp (2004), Popp (2006), and Yin and Chang (2020) examined the effects of induced technological change in energy-saving and low-carbon technology. They concluded that economic welfare improves if the model considers various energy R&D investments.

According to the report on world energy investments (IEA 2019), energy R&D investment amounted to \$122.7 billion in 2018, accounting for 6.66% of the overall energy investment. Despite the small share, R&D investment incubates early stage energy innovation, stimulates the improvement of energy storage (e.g., the lithium-ion battery), and encourages the development of emission reduction technology (e.g., renewable technologies and carbon capture and storage). This paper mainly focuses on two types of R&D investments: R&D investment in energy efficiency and R&D investment in backstop technology. The former enhances the energy supply chain (e.g., the energy production process and energy transmission process), providing more energy services with the same raw energy. The latter lowers the cost per unit of backstop technology (e.g., solar photovoltaic technology and wind power technology), which improves the comparative advantage of backstop technology and induces the energy transition from fossil fuels to backstop technology. The model in this paper reflects the unique feature of each type of R&D investment.

In the past few years, the energy R&D investments have been inadequate to curb carbon emissions sufficiently to meet the Paris Agreement (i.e., the 2°C policy). Twenty-four countries, including the US and the People's Republic of China, are engaging in a global initiative and have committed to doubling the public investment in clean energy R&D and fostering energy innovations. This paper considers how energy tax influences two types of energy R&D investment, which further affect economic welfare, carbon emissions, and climate change, under various emission abatement policies. Energy tax is a market-based instrument to adjust the energy R&D investments to the optimal level. The existing literature has pointed out that the optimal level of energy tax does not have to be equal to the carbon price. Hart (2008) considered the induced technological change and concluded that the optimal energy tax is higher than the carbon price with an undersupply of the energy-saving technology. Our study also concludes that the optimal energy tax does not equal the carbon price following the energy transition approach.

The energy use obeys the Ricardian principles, whereby production uses the energy with the lowest cost. The energy cost can be decomposed into four terms as follows.

$$EC = EXTRC + CONVC + SCRENT + CBPR$$

where EC , $EXTRC$, and $CONVC$ are the total energy costs, extraction cost, and conversion cost, correspondingly. $SCRENT$ represents the scarcity rent. $CBPR$ stands for the carbon price. The total energy costs equal the sum of the extraction cost, conversion cost, scarcity rent, and carbon price. The first two terms are exogenous,

reflecting the physical cost in the energy production process and energy transmission process. The resource with the lowest cost initially progressively loses its comparative advantage as fossil fuels have a limited resource stock and negative environmental externality. The scarcity rent and the carbon price are two factors that drive a rise in the energy cost.

We distinguish the optimal energy tax and the Pigovian tax. The optimal energy tax contains the scarcity rent and the carbon tax, while the Pigovian tax only considers the carbon tax. We explore the energy R&D investments, economic welfare, carbon emissions, and climate change in a modified top-down model given the above two tax regimes. Setting the energy tax equal to the Pigovian tax is insufficient, leading to sub-optimal outcomes. The impact is more significant before the energy use transits from fossil fuels to backstop technology, while the impact is moderate after the backstop technology fully replaces fossil fuels. Another finding is that the sub-optimal outcomes are worse with a more restrictive abatement policy, while they are moderate with a less stringent abatement policy.

The organization of this report is as follows. Section 2 describes the trends of total energy investment and energy R&D investment. We summarize the features of energy investment and R&D investment and discuss the trends extensively by energy types and by contributing sectors. Section 3 documents the key literature relevant to induced technological change and carbon tax. Section 4 develops the modified top-down model. We adopt a two-sector and multiple-energy framework in a climate economy model. Section 5 presents the policy regimes of energy tax and various emission abatement policies. Section 6 summarizes the results of R&D investments, economic welfare, and climate change under the optimal energy tax. Section 7 compares the results given two policy regimes of energy tax. Section 8 concludes this paper.

2. ENERGY INVESTMENTS AND ENERGY R&D INVESTMENTS

2.1 General Energy Investments

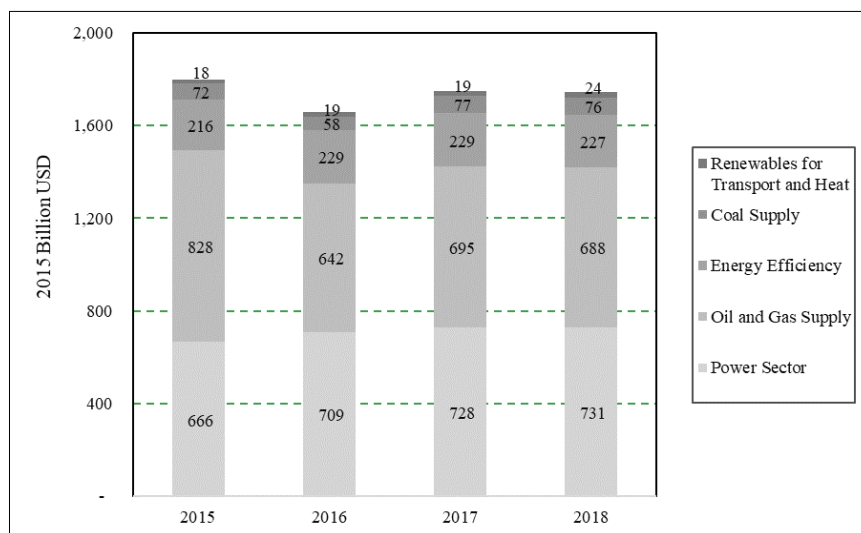
It is possible to categorize energy investments into four groups by sector: energy investment in the oil, gas, and coal sector, the power sector, energy efficiency, and renewables for transport and heat. Most of the energy invested in the oil, gas, and coal sector focuses on the upstream, which slows down the decline in the yield from the existing fields. It mitigates the gap between the fossil fuel supply and its demand in a sustainable development scenario.¹ A relatively small amount of energy investment in the above sector is for the downstream maintaining the refinery equipment. We can subcategorize the energy investment in the power sector into investment in electricity networks, renewables, nuclear, and general electricity generation. The energy investment in electricity networks enhances the electricity distribution and transmission. For example, some projects in electricity grids build up microgrids that are capable of controlling and operating the electricity network within a local area. The energy investment in renewables expands the capacity of renewable energy, such as solar photovoltaic (PV) systems and on-shore and off-shore wind power systems. The energy investment in nuclear power extends the operational life of existing nuclear

¹ Source: IEA. "The Oil and Gas Industry in Energy Transitions." <https://www.iea.org/reports/the-oil-and-gas-industry-in-energy-transitions>.

power plants.² Other investments in general electricity generation aim to maintain the power generation equipment. The energy investment in energy efficiency enhances the energy efficiency of the end-uses in buildings, industries, and transport. For example, energy-efficient building projects provide a significant reduction of the energy necessary for heating and cooling. The energy investment in renewables for transport and heat includes biofuels for transport and solar thermal heating installations.

Figure 1 shows the energy investment structure from 2015 to 2018. The total energy investment drops by 8% from 2015 to 2016, increases by 6% from 2016 to 2017, and remains stable from 2017 to 2018. The investment in the power sector leads, accounting for 40% of the overall energy investment. It increases continually from 2015 to 2018. The shares of the investment in renewables and electricity networks are 39% and 38%, correspondingly, in the total investment in the power sector in 2018. The investment in the oil and gas sector is the second largest, accounting for about 39% of the total energy investment, but it experiences a decline over the years. The share of the investment in energy efficiency is about 13% of the total energy investment, which stabilizes from 2015 to 2018. Other energy investments include the investments in the coal supply and renewables for transport and heat, which account for less than 6% of the total energy investment.

Figure 1: Energy Investment by Sector (2015 Billion USD)



Source: IEA (2016), IEA (2017), IEA (2018), IEA (2019).

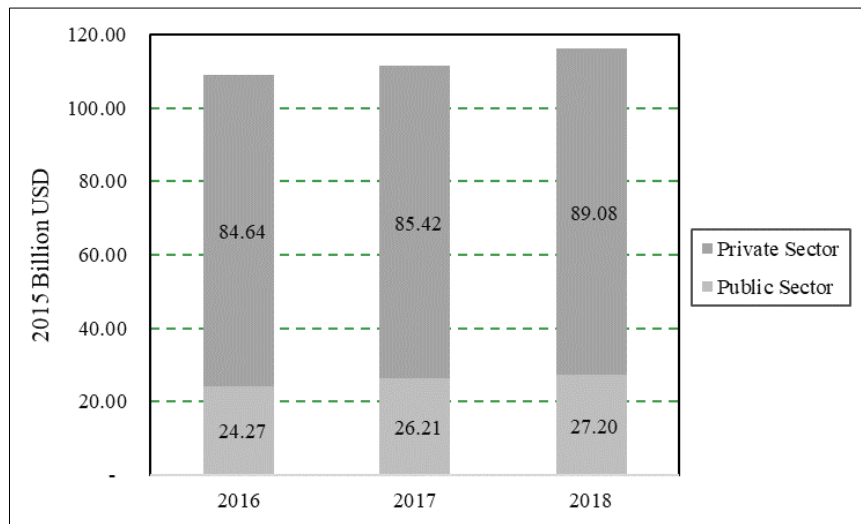
2.2 Energy R&D Investment

The energy R&D investment reaches \$122.7 billion (current currency) in 2018, accounting for 6.66% of the total energy investment. Figure 2 presents the energy R&D spending in the public sector and the private sector in 2016, 2017, and 2018. The public spending on energy R&D reaches \$28.7 billion (current currency) in 2018, accounting for one-fifth of the total energy R&D investment. In contrast, the corporate spending on energy R&D is \$94 billion (current currency), which is four times the public spending. The total energy R&D investment keeps increasing from 2016 to 2018.

² Source: IEA. "Nuclear Power in a Clean Energy System." <https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system>.

The public spending on energy R&D climbs by 8.0% from 2016 to 2017, while the rate of increase slows down to 2.8% from 2017 to 2018. The corporate spending on energy R&D remains stable from 2016 to 2017 while it increases by 4.3% from 2017 to 2018.

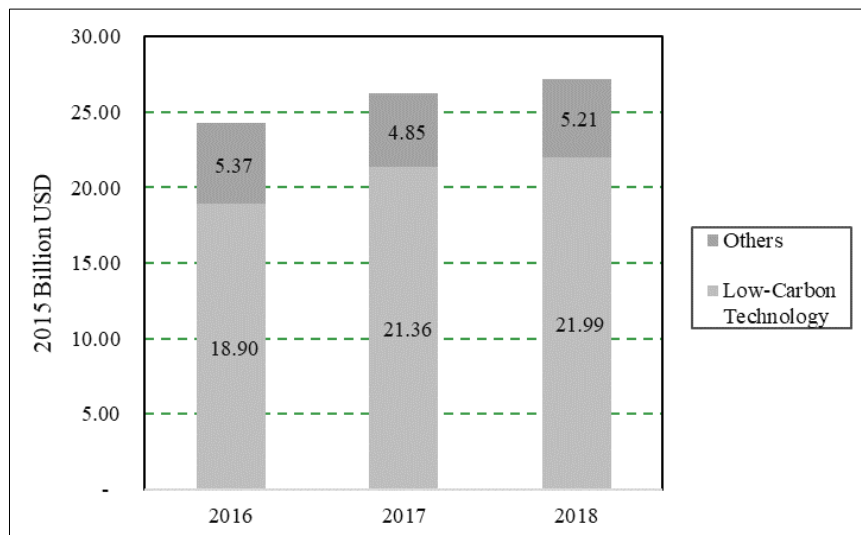
Figure 2: Energy R&D Investment in the Public Sector and the Private Sector (2015 Billion USD)



Source: IEA (2017), IEA (2018), IEA (2019).

Energy investment in research and development plays an important role in energy innovation. It enables energy systems to adopt new and affordable technologies. Energy R&D reshapes the energy system by improving the energy efficiency of the existing energy technology as well as by lowering the cost of advanced energy technology. For example, R&D investment in heating and cooling systems enables a building to be more energy efficient by improving the mechanical insulation, the air-sealed quality, and the performance of the glazing. Another example is that R&D investment in energy efficiency has induced wide adoption of light-emitting diode (LED) lights in recent years, with an energy-saving rate of more than 75% compared with incandescent bulbs. Other energy R&D investment includes spending in the electricity sector, such as electricity storage and smart electricity systems, and spending on better fuel combustion technologies.

Energy R&D also facilitates the slowing down of global warming and the meeting of environmental goals (e.g., the Paris Agreement). Figure 3 presents the public spending on energy R&D from 2016 to 2018. Among the total public spending on energy R&D investment, more than four-fifths of spending is on low-carbon technology in 2018, amounting to \$21.99 (constant 2005) billion. It jumps by 13.5% from 2016 to 2017 and slightly increases by 2.9% from 2017 to 2018. Low-carbon R&D investment enhances the existing low-carbon equipment (e.g., wind turbines) as well as provides funding for cutting-edge innovations, which are expensive at the early stage and have an uncertain market value. Low-carbon R&D investment improves the competitive advantage of low-carbon technology and facilitates the energy transition from fossil fuels to clean energy, which has a significant impact on emission abatement.

Figure 3: Governments' Energy R&D Investment (Constant 2015 Billion USD)

Source: IEA (2017), IEA (2018), IEA (2019).

Despite the increasing trend of energy R&D investment, scholars are still concerned that the investment in energy R&D is insufficient to meet the long-term goal of the Paris Agreement, which restricts the atmospheric temperature rise to under 2°C by 2100. Given the current energy R&D investment, new low-carbon technologies, such as carbon capture and storage (CCS), low-carbon freight transport, and energy efficiency, are not showing significant signs of being developed rapidly enough (IEA 2016). Less speedy adoption slows down the energy transition from traditional fossil fuels to clean energy. In 2015, 24 countries participated in a global initiative to accelerate public and private clean energy innovation to mitigate climate change.³ The member countries committed to doubling the R&D funding over 5 years and inducing an increase in private spending on low-carbon technology.

3. LITERATURE

This paper is mainly relevant to two streams of existing studies. Section 3.1 summarizes the key studies related to induced technological change and energy R&D investment. Section 3.2 documents the literature related to energy tax and energy R&D investment.

3.1 Induced Technological Change and Energy R&D Investment

One stream of literature relates to the role of energy R&D investment in economic growth. Popp (2004) considered endogenous technological change with R&D investment in energy efficiency in a climate–economy framework with environmental externalities. Like a physical investment, R&D investment facilitates the accumulation of knowledge in energy services. This study adopts a learning-by-researching function to model the evolution of energy knowledge. Energy R&D investment combines with the existing energy knowledge to boost energy technological change. The paper

³ Source: The Mission Innovation website. <http://mission-innovation.net/>.

concludes that ignoring R&D in energy saving leads to an underestimation of economic welfare. In addition, R&D in energy saving reduces the emission abatement cost.

Popp (2006) extended the research of Popp (2004) by endogenizing the technological change in backstop technology. He considered both R&D investment in energy efficiency and R&D investment in backstop technology. R&D investment in backstop technology boosts the energy knowledge of backstop technology, hence lowering the cost of backstop technology per unit of energy services. He concluded that there are larger welfare gains from R&D investment in backstop technology.

Sue Wing (2003) investigated the potential of carbon tax to induce technological change through the induced R&D using a computable general equilibrium (CGE) model. He examined the resource relocation and the accumulation of energy knowledge on the industry level and found that the impact of induced technological change is large and positive and that the input substitution effect, which mitigates most of the deadweight loss of the tax, dominates it.

Yin and Chang (2020) identified two types of R&D investment in energy-saving technology and backstop technology. They modeled the way in which R&D investment in backstop technology alters the energy transition from conventional energy to clean energy. The study added energy micro-foundations to the traditional climate–economy framework. It concluded that R&D investment enhances economic welfare and boosts the energy transition from fossil fuels to backstop technology. A more restrictive abatement policy hurts the welfare in the short term while improving it in the long term.

3.2 Tax and Energy R&D Investment

Another stream of literature has explored the interaction of energy tax (or carbon tax) and energy R&D investment from both the microeconomic and the macroeconomic perspective.

Baker and Shittu (2006) explored the effect of a random carbon tax on two types of energy R&D: energy R&D for emission reductions, which facilitates conventional energy's provision of more energy services in the production process and hence cuts carbon emissions, and energy R&D in backstop technologies, which lowers the cost of non-conventional energy. They adopted a microeconomic framework following the approach of profit maximization. Energy R&D for emission reduction increases first and then decreases gradually as the carbon tax increases. The increase is due to the substitution between energy R&D and conventional energy, while a high carbon tax curbs the use of the combination of energy R&D and conventional energy at the same time. Energy R&D for backstop energy increases only if the energy type chosen by a firm is flexible enough.

Hart (2008) examined the endogenous technological change in energy savings under carbon taxes in a growth model. Considering the technology spillovers, the Pigovian taxes are optimal only if the energy-saving technology and the production technology are symmetric. The optimal tax is above the Pigovian tax, inducing the catching up of energy-saving technology if the energy-saving knowledge is undersupplied compared with the production knowledge.

Peretto (2009) examined the impact of energy taxes on the aggregate R&D and welfare in a growth model with two sectors: the manufacturing sector and the energy production sector. Energy taxes relocate resources from the energy production sector to the manufacturing sector. The relocation increases the final goods in the manufacturing sector, hence inducing an increase in aggregate R&D. The welfare is a U-shaped curve, which declines in the short run due to a higher energy price while the

acceleration of total factor production (TFP) growth offsets it due to the induced technological change. This study analyzes the effect of energy taxes abstracting the environmental externality of carbon dioxide.

Lim and Kim (2012) investigated a combined policy of carbon tax and R&D subsidies in a CGE framework. They examined four scenarios: the business-as-usual scenario, a global carbon tax scenario, a scenario with R&D subsidies for knowledge services, and a scenario with both carbon tax and R&D subsidies. They concluded that R&D subsidies offset the negative impact of carbon tax on GDP growth. Both R&D subsidies and carbon tax shift the fuel mix toward less carbon-intensive energy. This paper also abstracts the environmental externality of carbon emissions from their model.

4. MODEL

4.1 Utility

Consider an infinite-horizon economy in a discrete-time model, in which a social planner makes consumption, physical investment, and energy R&D investment decisions to maximize the expected utility:

$$\max V = \sum_{t=0}^{\infty} L_t \cdot \frac{c_t^{1-\alpha}}{1-\alpha} \cdot (1+r)^{-t} \quad (1)$$

where r is the pure rate of the social time preference, $\alpha \in (0,1)$ is the coefficient measuring inequality aversion, L_t is the aggregate labor supply, and c_t is the consumption per capita. The consumption in this study is a broad concept that includes not only traditional market purchases of goods and services, like food and shelter, but also nonmarket items, such as leisure, cultural amenities, and enjoyment of the environment. This conventional feature is in line with most environmental economics research, such as Nordhaus (1994), Nordhaus (2014), Nordhaus and Boyer (2003), and Popp (2004). The social planner aims to maximize a social welfare function that is the discounted sum of the utility of the per capita consumption.

4.2 Production Sector

This study considers $N = 2$ sectors, using the index i , named the capital goods sector and the consumption goods sector. Each sector produces a good that can be used for investment or consumption. This disaggregation of production enables us to capture a meaningful energy transition pattern in different sectors and to build our results on realistic micro-foundations for energy use. Each sector produces goods i in period t using capital K_{it} , labor L_{it} , and energy service ES_{it} following a Cobb–Douglas form of the production function with capital and energy service shares $\beta_i, \gamma_i \in (0,1)$. A_t represents the total factor productivity. Our model considers the negative impact of the increase in the atmospheric temperature on the gross output. Specifically, a higher atmospheric temperature induces a smaller damage factor (Ω_t) and thus a smaller net output. The net output Y_{it} in sector i in period t is the gross output ($A_t K_{it}^{\beta_i} ES_{it}^{\gamma_i} L_{it}^{1-\beta_i-\gamma_i}$) times the damage factor Ω_t , deducting the energy cost EC_{it} , which equation (2) below shows:

$$Y_{it} = \Omega_t A_t K_{it}^{\beta_i} ES_{it}^{\gamma_i} L_{it}^{1-\beta_i-\gamma_i} - EC_{it} \quad (2)$$

We allocate capital goods Y_{1t} to various investments, including physical investment I_t , R&D investment in energy-saving RE_t , and R&D investment in low-carbon technology RB_t . Consumption goods Y_{2t} go to consumption C_t , which we use as a numeraire.

$$Y_{1t} = I_t + RE_t + RB_t \quad (3-1)$$

$$Y_{1t} = C_t \quad (3-2)$$

Capital stock accumulates over time through physical investment I_t produced in the capital goods sector.

$$\sum_i K_{it+1} = (1 - \delta_K) \sum_i K_{it} + I_t \quad (4)$$

where $\delta_K \in (0,1)$ is the rate of capital depreciation and $K_{i0} > 0$ is given.

We model the energy service ES_{it} as a constant elasticity of substitution (CES) aggregate of raw energy input ER_{it} and the knowledge stock of energy-saving technology H_{Et} . This study assumes that the knowledge stock of energy-saving technology and the raw energy are substitutes. Either the use of raw energy or the advances of the knowledge stock regarding energy-saving technology can meet the energy needs. This assumption is in line with Popp (2004), Popp (2006), and Yin and Chang (2020).

$$ES_{it} = A_E (a_E ER_{it}^\sigma + (1 - a_E) H_{Et}^\sigma)^{1/\sigma} \quad (5)$$

where the scale parameter $A_E > 0$, the weight parameter $a_E \in (0,1)$, and the substitution parameter $\sigma \in (0,1]$.

Raw energy combines carbon-based fossil fuels and low-carbon technology B_{it} (such as wind energy and solar energy), which is called backstop technology in most economic literature. This model considers $M = 3$ representative carbon-based fossil fuels in each sector, which it indexes with $J = P, W, G$, namely oil products P_{it} , coal products W_{it} , and natural gas G_{it} . The disaggregation of energy types enables us to investigate the pattern of the energy transition.

$$ER_{it} = \sum_J J_{it} + B_{it}, J = P, W, G \quad (6)$$

This study assumes a linear combination of different energy products as we can measure each energy production in the same unit, such as a barrel of oil equivalent (boe) or a ton of oil equivalent (toe). The assumption is in line with the literature related to the energy transition, such as Chakravorty et al. (1997), Chang (1999), and Yin and Chang (2020).

The initial resource stock $S_{j0} > 0$ restricts the depletion of carbon-based fossil fuels over time. This study assumes that the resource stock remains constant over the years. A limited resource stock induces a scarcity rent upon resource extraction. However, the available resources may change in the long run as the extraction technology improves or as new resource stock is discovered. This discussion is beyond our scope.

$$\sum_i J_{it} \leq S_{jt} - S_{jt+1} \quad (7)$$

The energy costs EC_{it} appearing in equation (2) are the sum of the cost per unit of each fossil fuel $p_{ijt} > 0$ and the cost per unit of backstop technology p_{ibt} with $p_{ib0} > 0$.

$$EC_{it} = \sum_j p_{ijt} J_{it} + p_{ibt} B_{it} \quad (8)$$

The cost of backstop technology p_{ibt} declines over time as the knowledge stock of backstop technology H_{bt} accumulates. Backstop energy, such as wind power and solar power, achieves higher efficiency levels and lower costs by increasing the installation capacity due to economies of scale.

$$p_{ibt} = \frac{p_{ib0}}{(H_{bt})^b} \quad (9)$$

where $0 < b < 1$ is a scale parameter. Thus, the increases in the knowledge stock of backstop technology lead to decreases in the cost of backstop technology, but they are less than proportional. This assumption is consistent with Popp (2006), Hart (2008), and Yin and Chang (2020).

The knowledge stock of the energy-saving technology and the backstop technology evolves similarly to the capital stock. Energy knowledge can be carried over from period t to period $t + 1$ with a depreciation rate δ_H . Knowledge creation depends on the existing energy knowledge and R&D investments in energy efficiency and backstop technology. We model the process of knowledge creation following the “learning-by-researching” approach, which Barreto and Kypreos (2004), Miketa and Schrattenholzer (2004), Popp (2004), and Popp (2006) adopted.

$$H_{mt} = (1 - \delta_H)H_{mt} + \varphi_{m1} R_{mt}^{\varphi_{m2}} H_{mt}^{\varphi_{m3}}, m = E, B \quad (10)$$

where $\delta_H \in (0,1)$, $\varphi_{m1} > 0$ is a scale parameter, and $\varphi_{m2}, \varphi_{m3} \in (0,1)$ are exponential parameters meaning that knowledge creation has diminishing returns on R_{mt}, H_{mt} .

4.3 Modeling Emissions and Regulation

Our study treats carbon emissions as by-products of fossil fuel combustion. Each unit of specific fossil fuels emits an amount $\epsilon_j, j = P, W, G$ tons of carbon independent of the processing method. We assume that different uses or processing methods do not

affect the carbon emissions while burning each unit of a specific fossil fuel, which is in line with Metcalf (2009). We present the total carbon emissions below.

$$EM_t = \sum_i \sum_J \epsilon_{Jit}, J = P, W, G \quad (11)$$

The carbon emissions enter the atmosphere and are involved in the carbon circulation among the atmosphere, the upper ocean, which serves as a quickly mixing reservoir, and the deep ocean, which we assume to be “an infinite sink for carbon” (Nordhaus, 1994). The accumulation of greenhouse gases (GHGs) forms a radiative force that drives up the atmospheric temperature. The increase in the atmospheric temperature harms the gross production through the damage factor Ω_t . We formulate the carbon exchange and the radiation process following Nordhaus (2014). The appendix contains the full equations of carbon circulation.

4.3.1 Tax Regime 1: Endogenous Optimal Energy Tax

When solving the above model optimally, the optimal energy tax contains the scarcity rent and the Pigovian tax. The scarcity rent reflects the limited stock of fossil fuels, that is, the stock constraint equation (7). The Pigovian tax reflects the negative externality of carbon emissions, that is, the carbon cycle constraint. Here, we determine the optimal energy tax endogenously.

4.3.2 Tax Regime 2: Exogenous Tax on Fossil Fuels

Governments impose a tax τ_t^F on fossil fuels. With tax τ_t^F , the energy cost in equation (8) becomes equation (12). A reduced lump-sum tax will compensate for the revenue collected through the tax on fossil fuels. As in section 4.3.1, the social planner does not include tax revenue in the optimization since it is a transfer payment.

$$EC_{it} = \sum_J (1 + \tau_t^F) p_{iJt} J_{it} + p_{iBt} B_{it} \quad (12)$$

On one hand, the tax changes the relative price of fossil fuels and backstop technology encourages the accumulation of knowledge on backstop technology H_{Bt} , further inducing a faster energy transition to clean energy. On the other hand, the tax increases the energy price of fossil fuels if they are the only form of energy that production uses. It also alters the relative price of fossil fuels and the energy knowledge stock of energy-saving technology H_{Et} . Thus, it can also stimulate the accumulation of H_{Et} and induce more efficient energy use.

5. POLICY REGIMES

This study investigates three emission abatement policies:

- (a) An optimal policy scenario in which the marginal cost of CO₂ reduction equals the marginal benefit from the emission abatement;
- (b) A 2°C policy scenario in which the atmospheric temperature change is below or up to 2°C above the pre-industrial levels, which is the goal of the Paris Agreement; we determine the emission control rate optimally to maximize the objective function subject to the temperature target;

- (c) A 1.5°C policy scenario in which the atmospheric temperature change is below or up to 1.5°C above the pre-industrial levels, which the IPCC proposed in its special report in 2018 (IPCC 2018); we determine the emission control rate optimally to maximize the objective function subject to the temperature target.

For each abatement policy, this study considers two energy tax policy scenarios:

- (a) A scenario with the optimal energy tax in which the energy tax equals the shadow price of carbon emissions (the Pigovian tax) plus the shadow price of the energy stock (the scarcity rent);
- (b) A scenario with a suboptimal energy tax in which the energy tax is set equal to the shadow price of carbon emissions. In this case, the energy tax is a pure Pigovian tax. The government only considers the negative environmental externalities while failing to consider the scarcity rent.

6. RESULTS: OPTIMAL ENERGY TAX

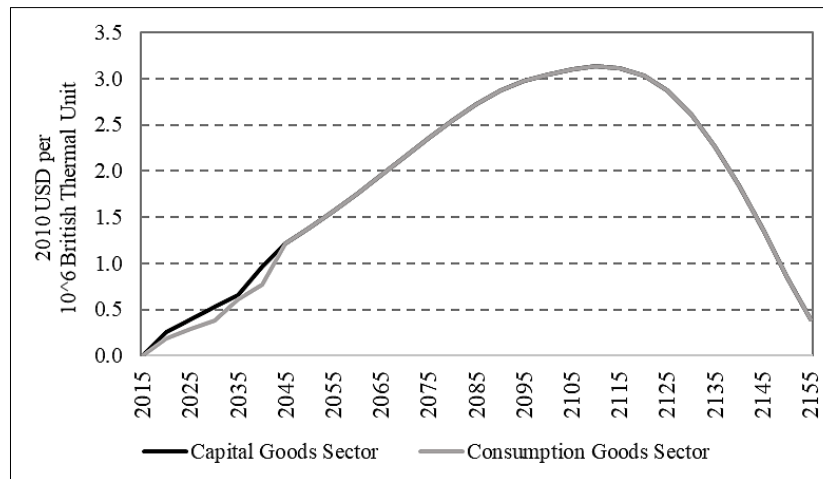
6.1 Pigovian Tax on Energy

Figure 4 presents the Pigovian tax on energy in two sectors in the optimal abatement policy scenario. The energy tax equals the carbon tax times the energy emission coefficient. First, the energy tax is associated with the carbon price, reflecting the environmental externality. The energy tax climbs from 2015 to 2110, reaching its highest point in 2110 and then falling from 2110 to 2160. This trend corresponds to the trends of temperature, showing the damaging impact caused by GHGs. Second, the energy tax on dirty energy (e.g., coal and coal products) is higher than the energy tax on clean energy (e.g., natural gas) given the same carbon price. The energy taxes in the two sectors are different before 2045 because they have different energy use patterns. The capital goods sector chooses oil and oil products followed by coal and coal products from 2015 to 2045, while the consumption goods sector chooses natural gas followed by oil and oil products. In the above period, the energy that the consumption goods sector uses always has a low emission coefficient, that is, it is cleaner, than that in the capital goods sector. Thus, the energy tax is lower in the consumption goods sector than in the capital goods sector from 2015 to 2045. After 2045, both sectors use the same energy. The two sectors have the same energy taxes after 2045.

6.2 R&D Investments

Table 1 summarizes the overall amount and the share of R&D investments in energy efficiency and backstop technology from 2015 to 2100 and from 2015 to 2165 given a Pigovian tax on fossil fuels. RE reaches \$1,374.72 billion by 2100 and \$1,860.60 billion by 2165, accumulatively accounting for 0.03% and 0.02%, correspondingly, of the total investment under the optimal abatement policy. The total RB achieves \$5,294.03 billion by 2100 and \$9,575.21 billion by 2165, accounting for 0.10% and 0.10%, correspondingly in the overall investment given the optimal abatement policy. RB has a leading role compared to RE from the amount approach, which is four times of RE under the optimal abatement policy. RE is stable provided different abatement policies. A more restrictive abatement policy can boost RB. With the 2°C policy and the 1.5°C policy, RB is 1.29 times and 1.46 times that with the optimal abatement policy from 2015 to 2100.

**Figure 4: Pigovian Tax on Energy in Each Sector
under the Optimal Abatement Policy
(2010 USD per 10^6 BTU)**

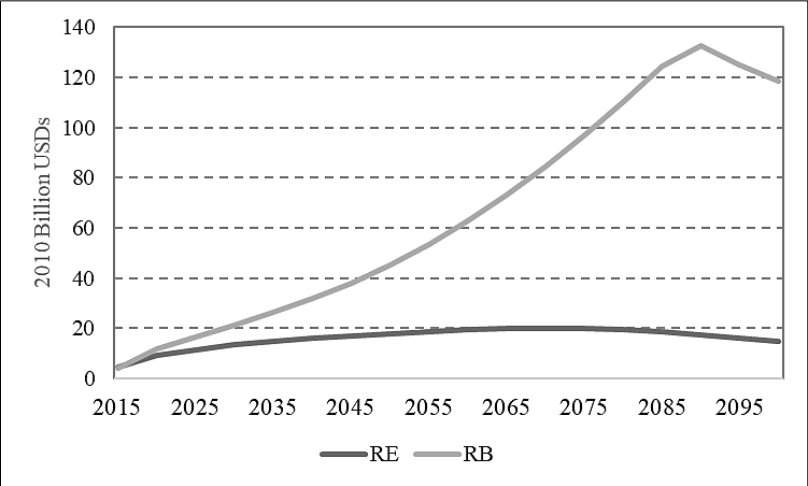


**Table 1: Amount and Share of R&D Investment in Energy Efficiency
and Backstop Technology**

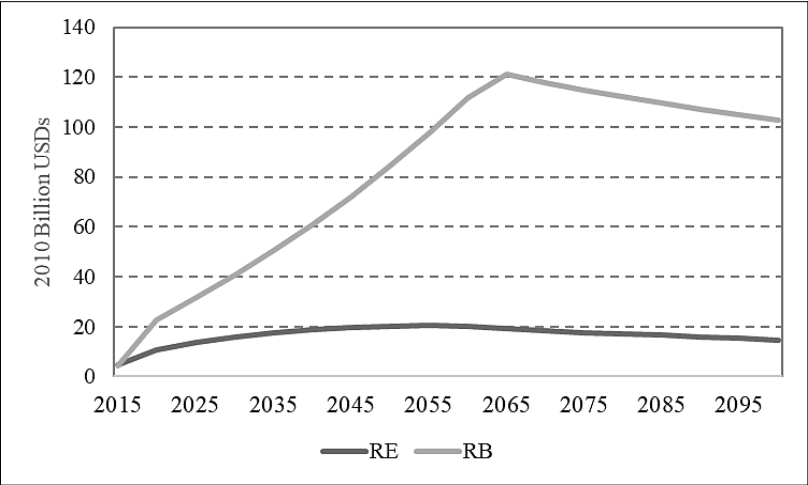
	Net Present Value (2010 Billion USD) 2015–2100	Net Present Value (2010 Billion USD) 2015–2165	Share in the Total Investment 2015–2100	Share in the Total Investment 2015–2165
RE				
Optimal policy	1,374.72	1,860.60	0.03%	0.02%
2°C policy	1,400.29	1,866.71	0.03%	0.02%
1.5°C policy	1,378.61	1,842.01	0.03%	0.02%
RB				
Optimal policy	5,294.03	9,575.21	0.10%	0.10%
2°C policy	6,818.39	10,295.47	0.13%	0.11%
1.5°C policy	7,736.79	11,367.46	0.15%	0.12%

Figure 5 presents the trending lines of R&D investments in energy efficiency and backstop technology by the end of this century given various abatement policies. The graph indicates the leading role of RB. RB keeps increasing until the backstop technology replaces fossil fuels. The spike occurs when the energy that both sectors use transits from fossil fuels to backstop technology. The highest amounts of RB are \$132.61 billion, which it achieves in 2090 under the optimal abatement policy, \$121.35 billion, which it reaches in 2065 under the 2°C policy, and \$111.83 billion in 2050, which is achieves under the 1.5°C policy. RE increases slowly, reaching its highest point before the energy replacement of backstop technology, and then declines slowly. The highest amount of RE is \$20.06 billion, which it achieves in 2070 under the optimal abatement policy, \$20.30 billion, which it reaches in 2055 under the 2°C policy, and \$19.10 billion in 2045, which it achieves under the 1.5°C policy.

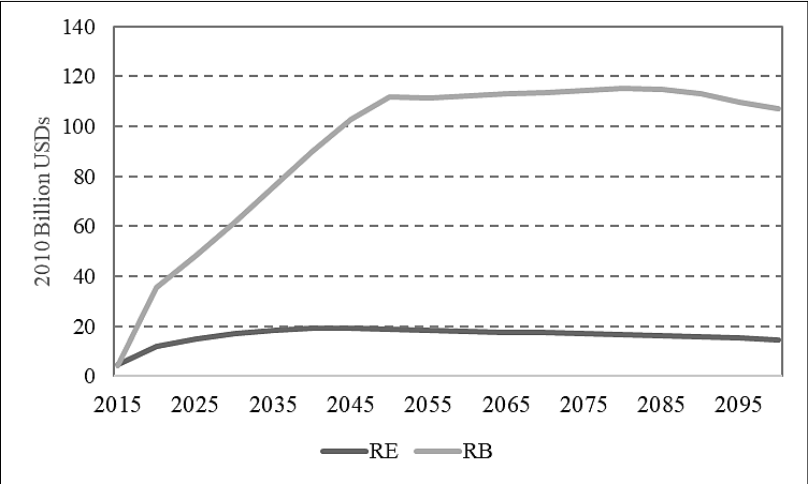
Figure 5: R&D Investments in Energy Efficiency and Backstop Technology by 2100



(a) Optimal Abatement Policy



(b) 2°C Policy



(c) 1.5°C Policy

6.3 Economic Welfare

Table 2 presents the GDP and consumption from 2015 to 2165. It divides the overall period into three sub-periods. Each sub-period contains 50 years. The GDP and consumption reach 34,013.91 and 24,417.42, correspondingly, under the optimal policy. The GDP, given the 2°C policy (or the 1.5°C policy), declines by 1.20% (or 2.51%) compared with the optimal policy. In the first hundred years (2015–2115), the optimal policy always leads to a higher GDP and consumption than the 2°C policy and the 1.5°C policy. However, in the last sub-period (2115–2165), the GDP and the consumption under the 2°C policy and the 1.5°C policy outpace that under the optimal policy. A more restrictive abatement policy leads to worse performance in the near term but a better performance in the long term. If the time horizon extends, a stringent abatement policy may induce greater economic welfare in the overall time horizon.

Table 2: GDP and Consumption (USD 2010 Trillion) in 2015–2065, 2065–2115, 2115–2165, and 2015–2165

2010 Trillion USD	2015–2065	2065–2115	2115–2165	2015–2165
GDP				
Optimal policy	8,798.03	12,677.58	12,538.29	34,013.91
2°C policy	8,543.82	12,145.60	12,917.57	33,607.00
1.5°C policy	8,087.40	12,055.34	13,017.84	33,160.58
Consumption				
Optimal policy	6,019.26	8,792.10	9,606.07	24,417.42
2°C policy	5,848.06	8,399.18	9,955.59	24,202.82
1.5°C policy	5,513.46	8,329.05	10,023.21	23,865.71

6.4 Energy Substitution, Carbon Emissions, and Climate Change

Table 3 presents the energy use sequence in the capital goods sector and the consumption goods sector. The energy sequence in the capital goods sector is oil, coal, and backstop technology, while that in the consumption goods sector is gas, oil, coal, and backstop technology. The backstop technology starts replacing fossil fuels in 2090 given the optimal abatement policy, in 2065 given the 2°C policy, and in 2045 given the 1.5°C policy.

Table 3: The Sequence of Energy Transition (Optimal Energy Tax)

Capital Goods Sector			
Optimal policy	2040 (oil to coal)	2090 (coal to backstop tech.)	
2°C policy	2050 (oil to coal)	2065 (coal to backstop tech.)	
1.5°C policy	2045 (oil to backstop tech.)		
Consumption Goods Sector			
Optimal policy	2035 (gas to oil)	2045 (oil to coal)	2095 (coal to backstop tech.)
2°C policy	2040 (gas to oil)	2055 (oil to coal)	2070 (coal to backstop tech.)
1.5°C policy	2050 (oil to backstop tech.)		

Figure 6 shows the trends in carbon emissions from 2015 to 2100. Carbon emissions climb under the optimal policy from 2015 to 2060 then decline after 2060 and eventually drop to zero in 2095. Given the 2°C policy, carbon emissions fall slightly from 2015 to 2035, rise slightly from 2035 to 2055, and then decline after 2060, reaching zero in 2070. With the 1.5°C policy, carbon emissions keep decreasing until they reach zero in 2055. We can decompose the reasons for the movement into two effects. First, the energy that production uses declines under a more restrictive abatement policy. Second, the energy transition to abundant fossil fuels leads to an increase in carbon emissions before the backstop technology fully replaces the fossil fuels because dirty fossil fuels (e.g., coal and coal products) are more abundant than clean fossil fuels (e.g., oil and oil products). When the first effect dominates the second effect, carbon emissions increase, and vice versa. We notice that energy substitution leads to a choppy change in carbon emissions under various abatement policies. Carbon emissions become zero after the energy that production uses fully transits from fossil fuels to backstop technology. Under the 2°C policy, production restores the use of oil after 2085, but it only accounts for a small share of the total energy use. Given the 1.5°C policy, production reverts to the use of coal after 2075, but it only accounts for a very small share of the total energy use.

Figure 6: Carbon Emissions (GtC) from 2015 to 2100

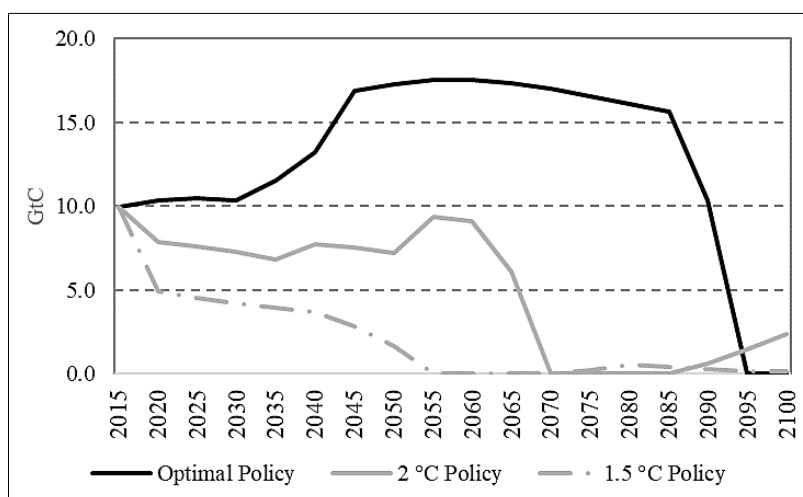
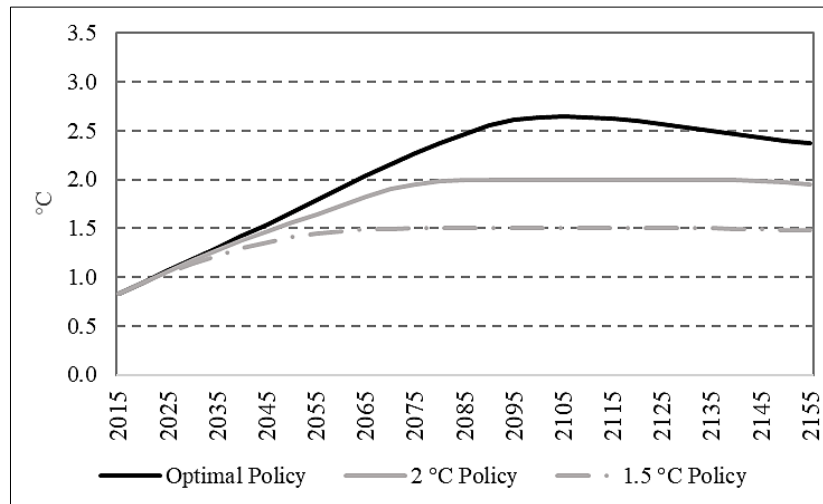


Figure 7 presents the atmospheric temperature given various abatement policies. The highest temperature is 2.6456°C in 2110 with the optimal policy, which is 0.6456°C (or 1.1456°C) higher than 2°C (or 1.5°C). The temperature hits the restrictive temperature level of 2°C (or 1.5°C) in 2090 (or 2075) given the 2°C (or the 1.5°C) abatement policy. The highest temperature occurs after the backstop technology substitutes fossil fuels. The delay time is about 20 years in the three abatement policies. It reflects a lagged effect of GHGs, which public policy agencies and environmental economists have observed. For example, the United States Environmental Protection Agency mentioned that carbon dioxide can stay in the atmosphere for 50 to 200 years.

Figure 7: Atmospheric Temperature (°C)

7. TAX COMPARISON: PIGOVIAN TAX VS OPTIMAL ENERGY TAX

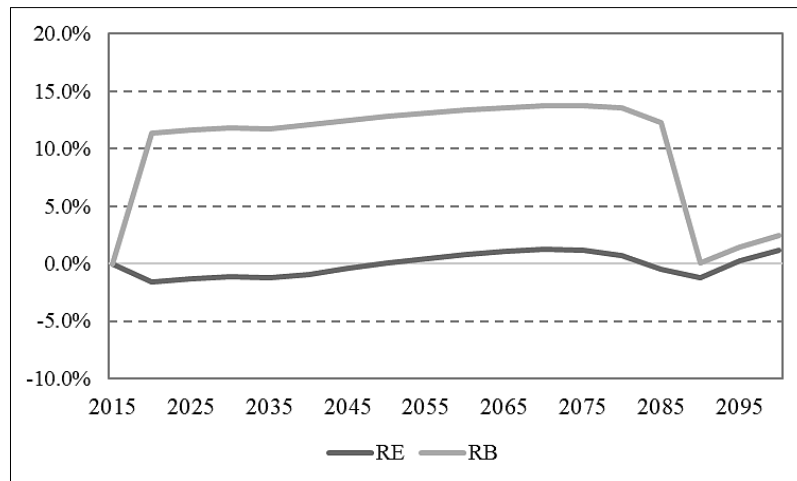
This section compares the case that sets the energy tax as 100% Pigovian tax and 105% Pigovian tax exogenously and the case that determines the optimal energy tax endogenously. The optimal energy tax contains both Pigovian tax and scarcity rent due to the limited resource stocks. The energy tax is an underestimation in the case that it is equal to the Pigovian tax. This section examines the impact of insufficient energy tax on R&D investments, economic welfare, energy substitution, and climate change.

7.1 R&D Investments

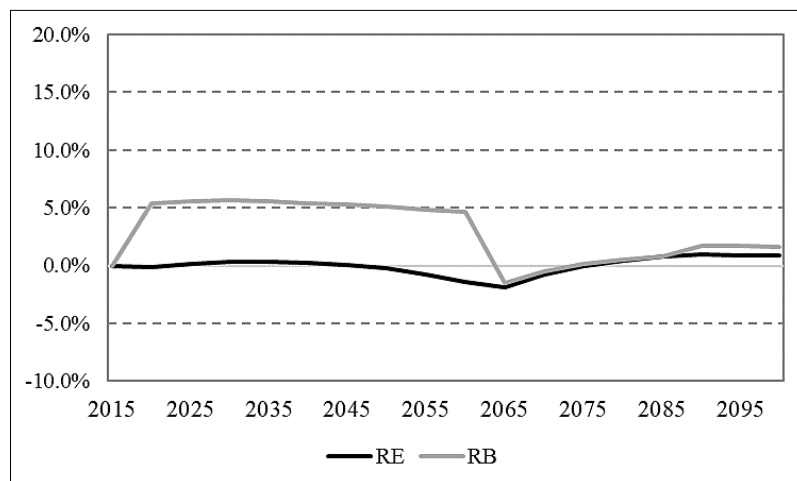
Figure 8 presents the relative change in R&D in the case that sets the energy tax exogenously as equal to the Pigovian tax compared with the case that determines the energy tax endogenously under various abatement policies. It shows the relative change in percentages. The relative change in RB is positive before the energy transition from fossil fuels to the backstop technology in the scenarios of optimal abatement policy and the 2°C policy. However, the relative change in RB is negative before the energy transition given the 1.5°C policy. Two drivers intervene in the relative change. The first driver encourages energy transition. The logic is that insufficient energy tax results in overuse of fossil fuels. RB needs to be higher to induce a lower cost of backstop technology and thus stimulate a faster transition to backstop technology to meet the abatement policy. The second driver is the abatement policy. A more stringent abatement policy reduces the energy use in production; thus, the constraint of some resource stock is not binding. A suboptimal energy tax hurts the output, leading to a lower RB. The relative change is positive if the first driver dominates the second one; otherwise, it is negative.

RE is a substitute for raw energy. The overuse effect leads to a lower RE initially given the optimal abatement policy and the 2°C policy. However, RE is a little higher after 2055. In addition, the relative change in RE is negative due to production using less energy under the 1.5°C policy.

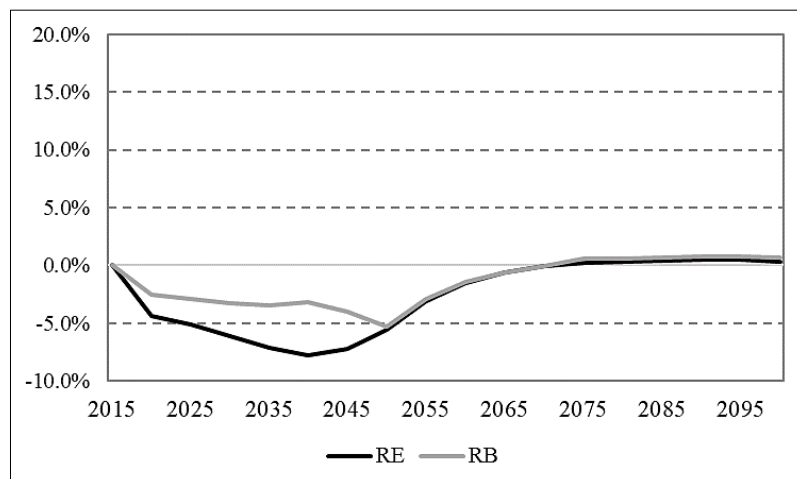
**Figure 8: Relative Change in R&D Investments
in Energy Efficiency and Backstop Technology
(Energy Tax as the Pigovian tax vs the Optimal Energy Tax)**



(a) Optimal Abatement Policy



(b) 2°C Policy

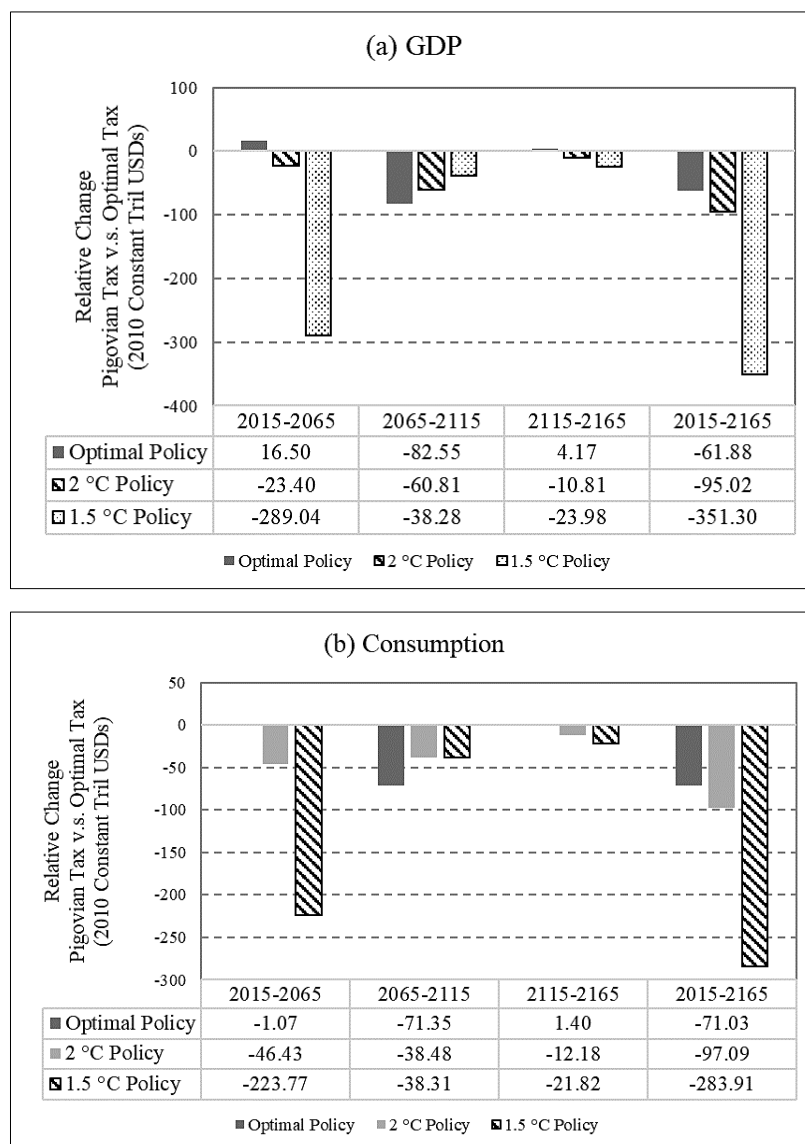


(c) 1.5°C Policy

7.2 Economic Welfare

Figure 9 presents the relative change in GDP and consumption between the case with the Pigovian tax only and the case with the optimal energy tax. In the entire time horizon, the relative differences in the GDP and consumption are negative under all the abatement policies. This indicates that imposing only a Pigovian tax is always suboptimal. The suboptimal tax hurts the GDP in the second sub-period most heavily under the optimal policy and the 2°C policy, while it has a severe negative impact on the GDP in the first sub-period under the 1.5°C policy. For consumption, the most negative impact of imposing the Pigovian tax only happens in the second sub-period given the optimal abatement policy but in the first sub-period with the 2°C policy and the 1.5°C policy. The suboptimal tax policy drives down the GDP and consumption more severely with a more stringent abatement policy.

**Figure 9: Relative Change in GDP and Consumption
(Pigovian Tax only vs Optimal Energy Tax)**



7.3 Energy Substitution, Carbon Emissions, and Temperature Change

Table 4 presents the energy transition sequence if imposing the Pigovian tax on energy. Compared with Table 3, the backstop technology substitutes fossil fuels in both sectors in the case with the Pigovian tax 5 years earlier than in the case with the optimal energy tax under the optimal abatement policy. The transition to backstop technology occurs 5 years earlier in the consumption goods sector in the case with the Pigovian tax than in the case with the optimal energy tax given the 2°C policy. The reason is that the insufficient energy tax induces the overuse of energy and thus higher economic growth given a less stringent abatement policy (such as the optimal abatement policy). The use of a larger amount of fossil fuels in production incentivizes higher R&D investments in backstop technology to improve the comparative advantage of backstop technology and to meet the abatement policy in the long run. In addition, high economic growth allocates more R&D investments to backstop technology, thus accelerating the energy transition to backstop technology. However, the energy transition remains the same in both tax cases given a more restrictive abatement policy (such as the 1.5°C policy), in which the abatement requirements have a great impact on energy transition rather than energy tax.

Table 4: The Sequence of Energy Transition (with Pigovian Tax Only)

	Capital Goods Sector		
Optimal policy	2040 (oil to coal)		2085 (coal to backstop tech.)
2°C policy	2050 (oil to coal)		2065 (coal to backstop tech.)
1.5°C policy	2045 (oil to backstop tech.)		
	Consumption Goods Sector		
Optimal policy	2035 (gas to oil)	2040 (oil to coal)	2090 (coal to backstop tech.)
2°C policy	2040 (gas to oil)	2050 (oil to coal)	2065 (coal to backstop tech.)
1.5°C policy	2050 (oil to backstop tech.)		

Figure 10 shows the relative change between the case with the Pigovian tax only and the case with the optimal energy tax. All the relative change is positive before the energy transition to the backstop technology under the three abatement policies. This means that the energy use is higher if the government sets the energy tax equal to the Pigovian tax compared with the case with the optimal energy tax. The downward spikes occur due to an early energy transition from fossil fuels to the backstop technology given the three abatement policies. The upward spikes indicate that some fossil fuels (e.g., oil and coal) return to use earlier under the Pigovian tax than under the optimal energy tax.

**Figure 10: Relative Change in Carbon Emissions:
The Case with Pigovian Tax Only vs the Case with the Optimal Energy Tax
(Base Case)**

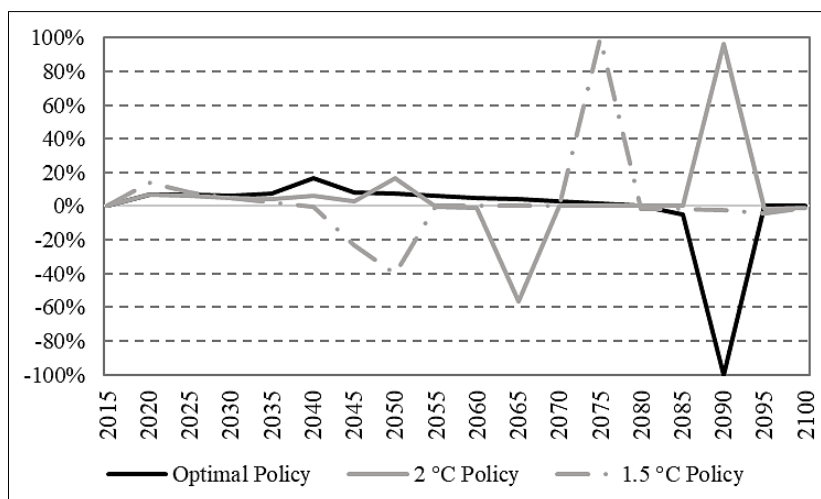
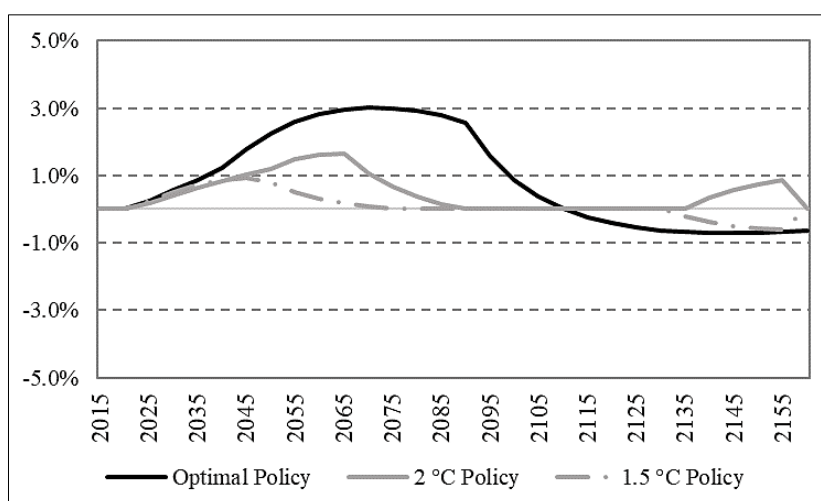


Figure 11 presents the relative change in temperature between the case with the Pigovian tax and the case with the optimal energy tax. Before 2110, the temperature is relatively higher in the case with the Pigovian tax than in the case with the optimal energy tax with the three abatement policies. This is due to higher carbon emissions in the early years, which is consistent with the trends in Figure 10. After 2110, the relative change in temperature is negative because of an early energy transition to the backstop technology given the optimal abatement policy and the 2°C policy. Coal use leads to a positive relative change with the 1.5°C policy after 2135.

**Figure 11: Relative Change in Temperature:
The Case with Pigovian Tax Only vs the Case with the Optimal Energy Tax
(Base Case)**



8. CONCLUSION

We explore the energy R&D investments, economic welfare, carbon emissions, and climate change in a modified top-down model in two tax regimes, the optimal energy tax and only the Pigouvian tax. The Pigouvian taxes experience an increase followed by a decrease from 2015 to 2155. The peak of the Pigouvian taxes is in line with the time of energy transition from fossil fuels to backstop technologies. The energy taxes in the capital goods sector are always no less than those in the consumption goods sector because the use of energy in the capital goods sector is emission intensive compared with the use of energy in the consumption goods sector.

The optimal energy taxes include the Pigouvian tax and the scarcity tax due to a limited resource stock. Given the optimal energy taxes, RB plays a leading role compared with RE. RB accounts for more than 0.10% of the total investments, while RE has a share of about 0.03% of the total investments under various abatement policies. Both RE and RB increase first and then decline under various abatement policies. The highest amount of RB is achieved when backstop technologies fully substitute fossil fuels. We check two indicators—GDP and consumption—of economic welfare. A more restrictive abatement policy hurts economic welfare more in the short term while boosting economic welfare in the long term. Backstop technologies fully replace fossil fuels automatically in 2095 given the optimal abatement policy, in 2070 with the 2°C policy, and in 2050 given the 1.5°C policy.

Two effects drive the movement of carbon emissions: the abatement policy effect and the energy transition effect. The first effect leads to a fast decline under a more stringent abatement policy. The second effect induces an energy transition to an abundant energy resource. The highest temperature occurs after the energy replacement of backstop technologies due to a delayed effect of carbon dioxide. The highest temperature is 3.0681°C under the optimal abatement policy, which is 1.0681°C higher than the temperature under the 2°C policy and 1.5681°C higher than the temperature under the 1.5°C policy.

We compare the case that exogenously sets the energy tax as 100% Pigouvian tax and 105% Pigouvian tax and the case that endogenously determines the optimal energy tax. RB is higher in the exogenous case given the optimal abatement policy and the 2°C policy, while it is lower in the exogenous case under the 1.5°C policy. RE is quite stable under the optimal abatement policy and the 2°C policy, while it experiences a decline under the 1.5°C policy due to the decline in output. Both GDP and consumption are lower in the exogenous case than in the endogenous case. The exogenous case accelerates the energy transition from fossil fuels to backstop technology by 5 years with various abatement policies. The carbon emissions are higher in the exogenous case than in the endogenous case before the energy transition to the backstop technology under the three abatement policies. Before 2110, the temperature is relatively higher in the case with Pigouvian tax than in the case with the optimal energy tax given the three abatement policies.

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