Energy R&D Investments and Emissions Abatement Policy

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ABSTRACT

The study examines the interactions of the energy R&D investments and the CO_2 abatement policy using an endogenous energy R&D climate-economy model. Energy R&D investments affect the carbon emissions directly through efficiency improvements and indirectly by changing the comparative advantages of resources. This study considers the R&D investments in energy efficiency and low-carbon technology and explores how energy R&D investments accelerate the energy transition from fossil fuels to low-carbon technology. Three policies of carbon abatements are considered, namely, the optimal policy, the 2 °C policy, and the 1.5 °C policy. From the perspectives of benefits and costs, the optimal policy leads to the least abatement costs compared to the other two abatement policies. This study indicates that the more restrictive the abatement policy is, the more severe economic damage is caused in the short run, but more economic welfare is gained in the long run.

Keywords: Energy R&D investments, Emissions abatement policy, Energy efficiency, Backstop technology, Energy substitution, Cost-benefit analysis, Climate change

https://doi.org/10.5547/01956574.41.6.dyin

1. INTRODUCTION

Climate-economy models attempt to estimate and compare the benefits and costs to slow down global warming. The molecules of carbon dioxide, once emitted from various sources such as combustion, stay in the atmosphere for 50 to 200 years.[1] When the long-term emissions abatement policy is dealt with, it is important to take into account the interaction between the emissions abatement policy and energy technological progress because the impact of energy technological progress is typically realized over a long-time horizon. Figure 1 shows how CO_2 emissions are affected by the energy technological progress driven by energy R&D investments.

The energy R&D investments can be categorized into two main groups: energy R&D investments in energy efficiency and energy R&D investments in backstop technology.[2] The R&D investments in energy efficiency enhance the energy supply chain such as production, transformation, and consumption to deliver more energy services given the same amount of primary energy. For

1. We refer to the 'Inventory of US Greenhouse Gas Emissions and Sinks' published by the United States Environmental Protection Agency.

2. Backstop technology is a concept corresponding to the exhaustible resources. It is defined as a new technology producing a close substitute to an exhaustible resource by using relatively abundant production inputs that are constrained by the reserves.

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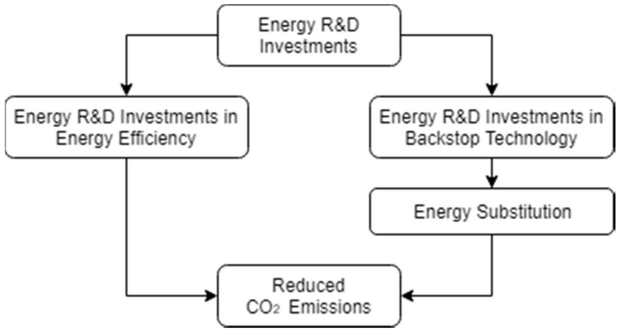
Figure 1: The Link between Energy R&D Investments and CO_2 Emissions



Source: Authors

example, the light-emitting dioxide (LED) technology saves 75% energy compared to traditional halogen (IEA, 2017a). Electric vehicles improve fuel efficiency compared to the internal combustion engine vehicles (IEA, 2017a). The improvement in energy efficiency reduces CO_2 emissions, thus directly affects the emissions abatement policy.

Energy R&D investments also expand the system scale of backstop technology, such as solar photovoltaic (PV) energy and wind energy (IEA, 2013, 2014). For example, the installed solar photovoltaic (PV) capacity has increased dramatically since 2010 than in the previous forty decades (IEA, 2017b). The amount of electricity generated by the PV system around the world grew by 50% in 2016. The PV's share of global electricity is expected to reach 16% by 2050 forecasted by (IEA, 2017b). Wind power deployment has more than doubled since 2008. Wind power generation targets 15% to 18% share of global electricity (IEA, 2015). System expansion lowers the operation and maintenance costs, hence, reduces the price per unit backstop energy, which enhances the competitive advantage of backstop technology.

Energy R&D investments in backstop energy affect CO_2 emissions indirectly through changing the energy compositions and energy substitutions. The energy compositions reflect the mixed energy demand in a specific sector. Table 1 indicates the heterogeneity of the energy composition among different sectors. Oil products are widely used in the transportation sector, coal and coal products are mainly used in the industry sector, and natural gas is largely used in the residential sector. Furthermore, the energy composition is dynamic rather than static. Figure 2 shows that the growth rate of each energy product is imbalanced over the years. Coal and coal products experienced a high growth rate from 2000 to 2010 but experienced a relatively low growth rate from 2010 to 2015. Solar and wind energy grow much faster than all the traditional energy resources did from 2005 to 2015. The changes in the energy composition indicate that inter-fuel substitutions are evident in different sectors. They result in changes in carbon emissions because of varying emissions coefficients of fossil fuels.[3]

The energy substitution is determined by the Ricardian comparative advantage that the energy with the comparative advantage, i.e., the one with the least cost, is first used in production. The comparative advantage of the energy changes endogenously over time due to two factors: the scarcity rent and the energy R&D investments. If a resource is not abundant, or it is scarce, the resource

3. Carbon dioxide emissions coefficient measures how much carbon dioxide is emitted when a British thermal unit (btu) of fuel is combusted. For example, 1 million btu of natural gas is combusted emitting 53.07 kilograms CO_2, while 1 million btu of coal (all types) is combusted emitting 95.35 kilograms CO_2. The data sources are provided by the EIA website. https://www.eia.gov/environment/emissions/co2_vol_mass.php

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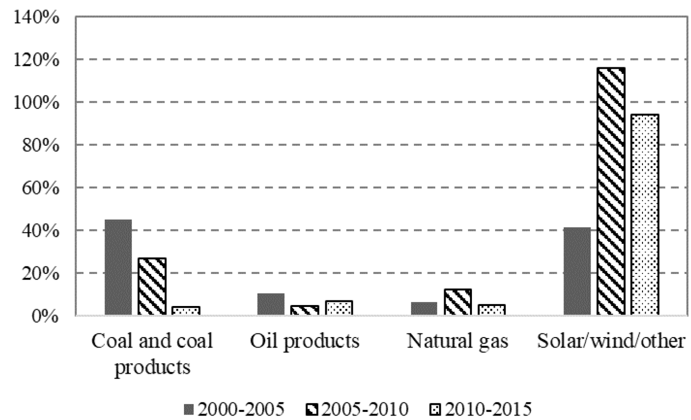
with an initial comparative advantage, i.e., a low cost, tends to lose its advantage as the scarcity rent increases. For example, coal was used at a lower cost than natural gas in the power sector. As natural gas booms in recent years, the scarcity rent of natural gas decreases significantly, which results in coal losing its comparative advantage and being replaced by natural gas in the power sector. The energy R&D investments in backstop energy lower the cost of the backstop technology and thus improve its comparative advantage compared to fossil fuels. It is interesting to see how the R&D investments in the backstop energy affect energy substitution and further alters the CO_2 emissions abatement policy.

Table 1: World's Energy Consumption by Energy Product by Sector, 2010 and 2015

	2010				2015			
Unit Mtoe	Coal and coal products	Oil products	Natural gas	Solar/wind/ other	Coal and coal products	Oil products	Natural gas	Solar/wind/ other
IND	803.9	316.1	495.8	0.2	826.2	298.9	529.8	0.4
TRA	3.4	2251.0	88.7	0.0	2.5	2491.0	97.6	0.0
RES	80.1	206.2	423.9	11.6	73.8	210.6	419.8	23.7

Source: World energy balances from IEA (2012a) and IEA (2017c). IND: industry sector, TRA: transport sector, RES: residential sector.

Figure 2: Growth Rate of Final Energy Consumption by Energy Product, Scope: World, 2000–2015



Source: IEA

We develop a new model named ENdogenous Energy R&D (ENER) model to incorporate the energy R&D investments and endogenous energy substitution into the climate-economy model. The ENER model has two distinct innovations. First, the model explicitly identifies the roles of R&D investments in energy efficiency and in backstop technology. It evaluates the impacts of energy R&D investments and the abatement policy on energy substitution, economic gains, and abatement costs. Second, it constructs a 2-sector 3-production-factor model that emphasizes the micro-foundation of energy substitution. The ENER model represents detailed energy demands that enable us to analyze inter-fuel substitution in each sector of an economy and to predict how soon the backstop energy replaces fossil fuels.

With the more realistic model, this study attempts to examine (a) the optimal policy of energy R&D investments, the optimal abatement policy, and the interaction of two; (b) the sequence of energy substitution; (c) economic gains and abatement costs, and (d) the climate impact. With the

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innovations made in the ENER model, this study expects to contribute to the literature in four areas. First, the study explores the different roles of two R&D investments and examines the interaction between energy R&D investments and the abatement policy. Second, the study investigates endogenous inter-fuel substitution given various energy R&D investments and abatement policies. We try to answer how soon the energy use will transit to backstop technology from fossil fuels. Third, the study estimates economic gains and abatement costs with the emissions abatement policies incorporating two types of energy R&D investments. Fourth, the study presents the possible temperature changes caused by CO_2 emissions and shows the control rates given different abatement policies.

The rest of the study is organized as follows. Section 2 presents a literature review focusing on three research streams related to the energy technological change, energy substitution, and climate-economy models. Section 3 formulates the model. Section 4 presents policy scenarios, data collection, and how the model is calibrated to deliver robust and significant results. Section 5 discusses the trajectory of energy R&D investments, the trajectory of abatement policy, and performance comparison with respect to the sequence of energy substitution, economic gains, abatement costs induced by various emissions abatement policies, and temperature changes. Section 7 concludes the study.

2. LITERATURE REVIEW

This study is closely related to three research streams. The first stream is energy technological progress. Jamasb and Kohler (2007) and Kahouli-Brahmi (2008) are excellent surveys summarizing how to model the learning curve for energy technology. Two approaches to model the technological progress are the 'learning-by-doing' approach and the 'learning-by-researching' approach. The 'learning-by-doing' approach (Benthem et al., 2008; Grübler and Messner, 1998; Liu and Wei, 2016; Manne and Richels, 2004) models that the energy cost is reduced by experience accumulation with a one-factor learning curve. The 'learning-by-researching' approach (Barreto and Kypreos, 2004; Miketa and Schrattenholzer, 2004) models that the energy cost is lowered by R&D investments and experience accumulation with a two-factor learning curve. To capture the feature of energy R&D investments, this study adopts a 'learning-by-researching' model. Extending the existing studies, this model explicitly identifies two types of energy R&D investments: R&D investments in energy efficiency and R&D investments in backstop energy. This study concludes that the two types of energy R&D investments play different roles in energy substitution and CO_2 reduction.

The second stream of research is related to the phenomenon called endogenous energy substitution. The endogenous substitution among resources is studied by Endress and Roumasset (1994) and Chakravorty et al. (2005). The specialization of resources according to demand is driven by Ricardian comparative advantage, which leads to an endogenous energy substitution. The endogenous energy substitution reflects heterogeneous demand and the simultaneous extraction of energy resources in an economy. Recent works related to energy transition include Court et al. (2018), Hartley et al. (2016), and Hartley and Medlock (2017). Their studies explore the displacement of fossil fuels by the alternative resources in the framework of growth model. Complementary to their work, our research examines the energy transition given various energy R&D investments and various abatement policies.

The third stream of research is related to the climate-economy model, which are from three broadly defined approaches: the top-down approach, the bottom-up approach, and the hybrid approach. Top-down models (Nordhaus, 1994, 2014; Popp, 2004) incorporate energy into a macroeconomic framework, where energy is a third production factor along with capital and labor. They

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evaluate emissions abatement policies and other macroeconomic variables in the macroeconomic and/or general equilibrium framework. Bottom-up models (EIA, 2008; Greene et al., 2004; Yi et al., 2019) have detailed representation of technologies of the energy system. They minimize end-use energy costs and choose energy transformation technology with the lowest costs. Hybrid models link the bottom-up model and the top-down model together. Most studies confine the research interests in the energy system of a specific sector, for example, the electricity sector (Dai et al., 2016; Hwang and Lee, 2015) and the transportation sector (Jaccard et al., 2004; Kloess and Müller, 2011).

Our model is a modified top-down model. Following the conventional top-down model, the ENER model incorporates a carbon cycle to the growth model and adopts a 150-year time horizon in the main analysis to consider the long-term environmental externality. Extending the traditional top-down models, the modified top-down model adds energy representatives. It specifies energy demands in two sectors, which enables examining the energy substitution in a macroeconomic framework. Especially it focuses on the displacement of fossil fuels by backstop technology. Unlike the hybrid model, the modified top-down model aggregates the energy system and presents the energy demands in a low resolution. It solves a general equilibrium problem from a global perspective rather than a partial equilibrium problem from a sector approach.

3. MODEL

This study develops the ENER model by adopting and modifying mainly the DICE model (Nordhaus, 2014) and the ENTICE model (Popp, 2004). Our model is a global model in which no specific region is considered. The new model considers energy substitution among fossil fuels, and between fossil fuels and backstop technology explicitly. It endogenizes the induced technological change (ITC) and combines the bottom-up model and the top-down model so that it can examine the concurrent impacts of ITC on energy substitution, economic gains, abatement costs, and climate change. The objective of the model is to maximize the discounted sum of per capita utility from consumption over 150 years subject to three constraints, namely, capital stock, resource stock and carbon stock in the atmosphere. The three constraints are called an economic constraint, an energy constraint, and an environmental constraint. The three constraints are set in a feedback loop. In the economic system, energy represents an input in the production function. Energy use links the economic system to the environmental system. In the environmental system, the energy-related emissions will drive up the concentration of CO_2 emissions in the atmosphere, leading to an increase in atmospheric temperature. A high atmospheric temperature eventually causes a negative impact on economic production.

The two sectors and multiple resources in the model identify the allocation of fuels in each sector. The first sector is the capital-goods production sector and the second sector the consumption-goods production sector. The multiple resources used in the model are oil products, coal products, natural gas, and backstop energy. Two types of ITC are considered in the ENER model, which is geared to improve energy efficiency and to reduce the costs of using backstop technology. The R&D investments affect the resource use directly and indirectly, which in turn affect the benefits and costs caused and altered by an abatement policy through the resource use. The time frame of the analysis is from 2015 to 2165 covering 150 years and the entire time horizon is divided by thirty periods. Each period has five years. The following sub-sections present the details of the model in sequence, the objective function of the model followed by three constraints, namely, economic constraints, energy constraints, and environmental constraints. The on-line supplementary materials present a list of all equations, variables, and parameters considered in the model.

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3.1 Objective Function of the Model

The objective function is to maximize the net present value of the population-weighted utility of per capita consumption over time T (T=30) as shown in equation (1). The form of the objective function is a standard representation of the economic growth model.

$$\max V = \sum_{t=1}^{T} L_t \cdot \frac{c_t^{1-\alpha}}{1-\alpha} \cdot \left(1+r\right)^{-t} \tag{1}$$

where L_t is the population to reflect the labor used in production at time t. c_t represents the per capita consumption at time t. α is the coefficient that measures inequality aversion. r is the pure rate of social time preference (per unit time). $\frac{c_t^{1-\alpha}}{1-\alpha}$ measures the utility of an individual at time t. $\left(1+r\right)^{-t}$ represents a social time preference discount factor (per period).

3.2 Economic Constraints

This study develops a two-sector model to represent the net output in the capital-goods production sector ($Q_{1,t}$) and the net output in the consumption-goods production sector ($Q_{2,t}$). Total net output (Q_t) is the sum of $Q_{1,t}$ and $Q_{2,t}$ as shown in equation (2). i represents the sector type.

$$Q_t = \sum_{i=1,2} Q_{i,t}, i = 1,2 \tag{2}$$

In each sector, the production function, i.e., $A_t K_{i,t}^{\beta_i} ES_{i,t}^{\gamma_i} L_{i,t}^{1-\beta_i-\gamma_i}$, takes the Cobb-Douglas form with three input factors: the physical capital stock ($K_{i,t}$), the labor ($L_{i,t}$), and the effective energy services ($ES_{i,t}$), where A_t reflects the exogenous technological change, and β_i and γ_i are the elasticity parameters of the capital stock and effective energy services. The production function makes the energy services as the third input factor. It enables us to study the energy substitution in each sector explicitly.

The net output ($Q_{i,t}$) in each sector is the gross output, i.e., $A_t K_{i,t}^{\beta_i} ES_{i,t}^{\gamma_i} L_{i,t}^{1-\beta_i-\gamma_i}$, times the damage factor (Ω_t) deducted by the abatement costs, i.e., $\Lambda_t \cdot A_t K_{i,t}^{\beta_i} ES_{i,t}^{\gamma_i} L_{i,t}^{1-\beta_i-\gamma_i}$, and the energy costs ($CE_{i,t}$), as shown in equation (3), where Λ_t is the parameter of emissions-control rate. The damage factor (Ω_t) is a variable negatively related to the atmospheric temperature, which reflects the damage impact of the high temperature on the net output. Specifically, a higher atmospheric temperature induces a smaller damage factor (Ω_t), thus a less net output. Λ_t reflects the effect of abatement policy. On one hand, a more restricted abatement policy leads to a larger Λ_t, thus, higher abatement costs in period t; on the other hand, it also leads to a lower atmospheric temperature in period $(t+1)$, thus, a smaller damage factor (Ω_{t+1}). The net output function in equation (3) explicitly takes into account three effects: the damage effect due to the increase in atmospheric temperature, the effect of abatement cost due to the abatement policy, and the effect of energy cost. The energy cost ($CE_{i,t}$) is formulated in detail in subsection 3.3.

$$Q_{i,t} = \Omega_t \left(1-\Lambda_t\right) A_t K_{i,t}^{\beta_i} ES_{i,t}^{\gamma_i} L_{i,t}^{1-\beta_i-\gamma_i} - CE_{i,t}, i = 1,2 \tag{3}$$

The net output in the capital-goods production sector ($Q_{1,t}$) is allocated to the investments in physical capital (I_t), the R&D investments in energy efficiency ($R_{E,t}$), and the R&D investments in backstop technology ($R_{B,t}$), which is shown in equation (4). Equation (4) characterizes the allocation of two types of energy R&D investments explicitly, which enables examining the optimal policy of

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the energy R&D investments. The net output of the consumption-goods production sector ($Q_{2,t}$) is allocated to consumption (C_t), which is used as a numeraire. It is shown in equation (5).

$$Q_{1,t} = I_t + R_{E,t} + R_{B,t} \tag{4}$$

$$Q_{2,t} = C_t \tag{5}$$

3.3 Energy Constraints

The effective energy services ($ES_{i,t}$) that are used in production shown in equation (3) are a combination of the resource ($ER_{i,t}$) and the knowledge stock of energy transformation ($H_{E,t}$) shown in equation (6). Assume that $ER_{i,t}$ and $H_{E,t}$ are substitutes in a CES form, where ρ is the elasticity. The above assumption is in line with Popp (2004) and Popp (2006).

$$ES_{i,t} = \left(ER_{i,t}^{\rho} + H_{E,t}^{\rho}\right)^{1/\rho}, i = 1,2 \tag{6}$$

The primary energy ($ER_{i,t}$) is expressed as the sum of four types of energy products: oil products ($P_{i,t}$), coal products ($W_{i,t}$), natural gas ($G_{i,t}$), and backstop energy ($B_{i,t}$) shown in equation (7). Assume they are a linear combination since each energy production can be measured in the same unit, such as barrel of oil equivalent (boe) or ton of oil equivalent (toe). The assumption is in line with Chang (1999). This model considers four types of energy explicitly enabling us to explore how one energy substitutes the other within the fossil fuels and between fossil fuel and the backstop technology.

$$ER_{i,t} = P_{i,t} + W_{i,t} + G_{i,t} + B_{i,t}, i = 1,2 \tag{7}$$

The total amount of each fossil fuel consumed in overall periods is less than the initial resource stock as shown in equation (8), where $S_{J,0}$ represents the initial stock of resource *J* where *J=P, W, G* representing the oil products, the coal products, and the natural gas. Equation (8) indicates the limited stock of fossil fuels leading to a scarcity rent upon extraction. This assumption is in line with Chakravorty et al. (1997), Chang (1999) and Chakravorty et al. (2005).

$$\sum_{t=1}^{T}\left(\sum_{i=1,2} J_{i,t}\right) \leq S_{J,0}, J = P, W, G \tag{8}$$

Energy costs ($CE_{i,t}$) appearing in equation (3) are the sum of the cost per unit of each energy ($z_{i,J,t}, J = P, W, G, B$) as shown in equation (9).[4]

$$CE_{i,t} = z_{i,P,t}P_{i,t} + z_{i,W,t}W_{i,t} + z_{i,G,t}G_{i,t} + z_{i,B,t}B_{i,t}, i = 1,2 \tag{9}$$

The cost of backstop technology ($z_{i,B,t}$) declines over time since the knowledge stock of backstop technology ($H_{B,t}$) increases as shown in equation (10), where b is a scale parameter. For example, as people gain more knowledge about utilizing solar energy in an effective and less costly method, the cost of solar energy will decrease. Equation (10) is in line with the evolution of the cost of backstop technology in Popp (2006).

4. Energy costs has four components: extraction cost, conversion cost, scarcity rent and the shadow price of carbon. Extraction cost and conversion cost are explicitly presented in the model. The scarcity rent is implicitly reflected in the model as the model sets the stock of each energy resource and the level of stock decreases over use and time. The shadow price of carbon is also implicitly reflected in the model as it is a dual variable. Note that the extraction cost of backstop technology is zero since the procedure does not consist extraction.

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$$z_{i,B,t} = \frac{z_{i,B,0}}{\left(H_{B,t}\right)^{b}} \tag{10}$$

The energy knowledge evolves as shown in equation (11), where δ_H is the depreciation rate of energy knowledge and h is the function of knowledge creation. Energy knowledge ($H_{m,t}$) in period t is the carried-over knowledge from period *(t–1)*, i.e., $\left(1-\delta_H\right)H_{m,t-1}$, plus the innovated knowledge, which is the function of energy R&D investments and the knowledge stock. The energy knowledge accumulates similarly to the physical capital stock. It is modeled in the same way as capital obsoleting and accumulation.

$$H_{m,t} = \left(1-\delta_H\right)H_{m,t-1} + h\left(H_{m,t-1}, R_{m,t-1}\right), m = E, B \tag{11}$$

$$h\left(R_{m,t}\right) = \varphi_{m,1} R_{m,t}^{\varphi_{m,2}} H_{m,t}^{\varphi_{m,3}}, m = E, B \tag{12}$$

The knowledge creation depends on the existing knowledge stocks and the energy R&D investments, shown in equation (12), where $\varphi_{m,n}, m = E, B, n = 1,2,3$ are parameters in the knowledge creation. Equation (12) adopts a 'learning-by-researching' approach to model the process of knowledge creation, which is in line with Barreto and Kypreos (2004), Miketa and Schrattenholzer (2004), Popp (2004), and Popp (2006).

The environmental constraints have similar settings in Chang (1999) and Nordhaus (2014). Environmental constraints capture the radiation effect and the carbon exchange among the atmosphere, upper ocean, and lower ocean. This section omits the equations of the environmental constraints in detail for the sake of conciseness. The on-line supplementary materials include a full list of equations, which includes environmental constraints.

4. POLICY SCENARIOS, DATA, AND CALIBRATION

4.1 Policy Scenarios

This study considers four scenarios for each abatement policy as follows:

(a) A business as usual (BAU) scenario where no emissions-abatement policy is considered;
(b) An optimal policy scenario in which the marginal cost of CO_2 reduction equals the marginal benefit from the emissions abatement;
(c) A 2 °C policy scenario in which the atmosphere temperature change is below or up to 2 °C above the pre-industrial levels, which is the goal of the Paris Agreement; the emissions-control rate is determined optimally to maximize the objective function subject to the temperature target;
(d) A 1.5 °C policy scenario in which the atmosphere temperature change is below or up to 1.5 °C above the pre-industrial levels, which is proposed by IPCC in the special report in 2018[5] (IPCC, 2018); the emissions-control rate is determined optimally to maximize the objective function subject to the temperature target.

5. The special report "Global warming of 1.5 °C" indicates that the climate-related risks are much higher if the global warming exceeds 1.5 °C. Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (high confidence).

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Each scenario considers four cases of energy R&D investments:

i. A basic case does not consider any energy R&D investments. The knowledge stock of the energy efficiency and the backstop technology are fixed;
ii. A case with energy R&D investments only in energy efficiency (RE) that incorporates the change of the knowledge stock of energy efficiency, but the cost of backstop technology is unchanged over time;
iii. A case with energy R&D investments only in backstop technology (RB) in which the cost of backstop technology declines over time, but the knowledge stock of energy efficiency remains fixed;
iv. A case with energy R&D investments in both energy efficiency (RE) and backstop technology (RB) in which the two types of R&D investments bring efficiency improvement and reduce the cost of backstop technology, respectively.

4.2 Data and Calibration

This study calibrates the parameters in the economic system and the energy system. In the economic system, the ENER model adopts a two-sector model. The key parameters in the two-sector model are the elasticity parameters of the capital input, the energy input, and the labor input in the production function of each sector, i.e., β_i , γ_i, and $1-\beta_i-\gamma_i$, *i=1,2*. The elasticity of labor ($1-\beta_i-\gamma_i$) equals to labor costs ($w_{i,t}L_{i,t}$) divided by the output ($Y_{i,t}$). The elasticity of energy (γ_i) equals to energy costs divided by the output ($Y_{i,t}$). We use U.S. data for calibration. The aggregate data are from the Economic Report of the President, 2010 (EPP). The structural data are from the Economic Report of the President (EPP), and the BEA, National Income and Product Accounts, Section 6 – Income and Employment by Industry (NIPA). The initial output (Q_0) is chosen to match the GDP of the world in the World Bank database. The initial total factor productivity ($A_{i,0}$) and the growth rate of TFP are solved to match the GDP in 2025, and 2035 that are collected from the World Bank's latest database and the MIT Joint Program Energy and Climate Outlook 2014. The initial capital stock (K_0) and the depreciation rate of the capital stock (δ_K) are in line with the DICE–16 model, which is the most updated version. The initial population (L_0) and the growth rate of the population are solved to match the World Bank database and the MIT Joint Program Energy and Climate Outlook 2014.

In the energy system, the initial reserves of fossil fuels are collected from the BP Statistical Review of World Energy 2016 (BP, 2016). The extraction cost and conversion cost of each resource are in line with Chakravorty et al. (1997). Initial energy R&D investments in energy efficiency and in backstop technology, $R_{E,0}$ and $R_{B,0}$, are estimated based on the proportion of energy R&D investments in the total GDP in the OECD countries provided by the IEA Energy Technology R&D Statistics (IEA, 2016).[6] The initial knowledge stocks ($H_{E,0}$ and $H_{B,0}$) are consistent with the ENTICE-BR model. Parameter $\varphi_{m,3}, m=E,B$ is taken from the ENTICE-BR model so that the value of elasticity falls slowly in the near future due to diminishing returns to R&D. $\varphi_{m,1}$ and $\varphi_{m,2}\left(m=E,B\right)$ are estimated to fit the change of R&D investments in energy efficiency and backstop technology between 2005 to 2015 based on the IEA Energy Technology R&D Statistics (IEA, 2016). The substitution ratio between raw energy and energy efficiency (ρ) follows the rate in the ENTICE-BR model. Parameter *b* is estimated to fit the paths of backstop energy cost suggested by Technology Roadmap

6. The proportion of RE in the share of GDP is 0.0037% in 2005 and 0.0082% in 2015 in the OECD countries, while the percentage of RB in the share of GDP is 0.0031% in 2005 and 0.0081% in 2015 in the OECD countries.

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covering wind energy, solar photovoltaic energy, and hydropower published by IEA (IEA, 2013, 2014, 2012b).

In the environment system, the concentration parameters in carbon cycle equations are taken from the DICE–16 model (Nordhaus, 2014) to guarantee that the environmental parameters are in line with the latest estimation. We estimate the parameter of the equilibrium CO_2 doubling (σ_F), and the parameter of equilibrium temperature impact ($\sigma_{F,eq}$) based on IPCC (2014).

Existing studies (Hu et al., 2012; Nordhaus, 2014) suggests that the environment-related integrated models, such as the DICE model, is relatively robust in ranking policies even if the ambiguities in the key parameters occur. However, the environment-related integrated model is sensitive to the mean values of the key parameters (Hu et al, 2012; Hatase and Managi, 2015). This property suggests that the ENER model can generate a robust policy of CO_2 abatement and energy R&D investments given accurate mean values of key parameters as illustrated above.

5. RESULTS AND DISCUSSIONS

The ENER model presents answers to three questions: (a) What is the optimal trajectory of energy R&D investments over the time span from 2015 to 2165? How does the emissions abatement policy affect the optimal trajectory of energy R&D investments? (b) What is the optimal abatement policy over the time span from 2015 to 2165? How do energy R&D investments influence the optimal abatement policy? (c) What is the system performance in terms of energy substitution, economic gains, abatement costs, and temperature change under different policy scenarios?

5.1 The Trajectory of Energy R&D Investments

This subsection first interprets the role of energy R&D investments in the production process. Second, it presents the total net present value of the energy R&D investments over 150 years under four abatement policies – no policy, the optimal policy, the 2 °C policy, and the 1.5 °C policy. Third, it examines the interaction of two types of energy R&D investments. Fourth, it explores how abatement policies affect RE and RB in case iv. We choose case iv as a representative because the amount of RE and RB does not change much under various R&D policy scenarios. We restrict our attention to R&D projection within the time span from 2015 to 2100 because the near-term receives more concerns from policymakers.

This study explicitly identifies the heterogeneous roles of energy R&D investments. RE is to accumulate the knowledge stock on energy efficiency (HE) and further to improve the amount of energy service in the production given the same amount of primary energy (ER). The complementary effect between primary energy and the knowledge of energy efficiency makes the path of RE positively related to the amount of primary energy. A higher amount of primary energy used in production leads to a higher level of energy R&D investments in energy efficiency. RB is to expand the system scale of the backstop technology and further to lower the cost of backstop technology. RB changes the comparative advantage of energy costs among various resources and enables backstop technology to replace fossil fuels earlier.

Figure 3 shows the total present value of all R&D investments from 2015 to 2165 in case ii, iii, and iv. Total R&D investments are the highest in case iv (with RE and RB) followed by case iii (with RB only), and by case ii (with RE only). R&D investments in backstop technology account for 80 % share in the total R&D in case iv (with RE and RB) meaning that RB has a leading role

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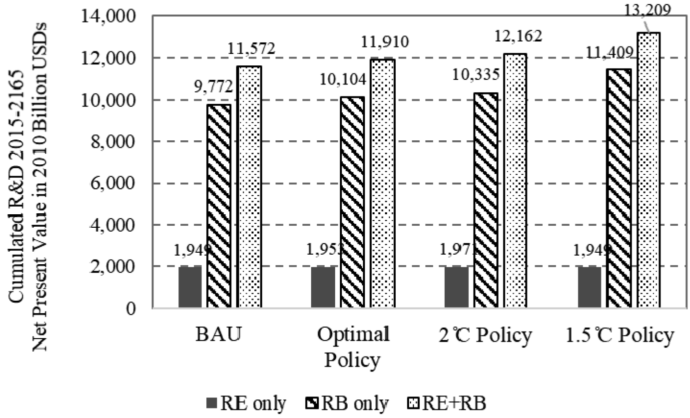
compared to RE. RE is not affected by the abatement policy much, while RB is effectively boosted by a restrictive abatement policy.

Figure 3: Total Energy R&D Investments over 2015–2165



Shown here are the net present value of the cumulated energy R&D investments in case ii) RE only, case iii) RB only, and case iv) RE and RB.

Next, this study examines the interaction of two types of R&D investments. We focus on the near-term interaction from 2015 to 2100, which is in line with the interests of most environmental policymakers, such as the IPCC group. Figure 4 presents the relative change of RE and RB given different R&D policies. The relative change of RE between case iv and case ii measures the impact of RB on RE, and the relative change of RB between case iv and case iii measures the impact of RE on RB. The negative relative change indicates that there is a crowd-out effect between RE and RB. The reduction of RE caused by RB is more than the reduction of RB caused by RE meaning that RB has a leading role compared to RE. The reduction of RE caused by RB is stronger under a restrictive abatement. The reduction of RB caused by RE is weak and almost the same across various abatement policies. Both facts indicate that RB is more effective than RE to facilitate meeting a stringent emissions requirement, which is in line with the observation in Figure 3. Figure 4 (a) also indicates that RB rules out RE more significantly in the late period, while Figure 4 (b) shows that the reduction of RE is steady over the time span from 2015 to 2100.

Last, this study examines the impact of abatement policy on energy R&D investments from 2015 to 2100. Figure 5 clearly shows that a restrictive abatement policy boosts both RE and RB in the early period from 2015 to 2040. However, it induces less RE and RB in the late period from 2075 to 2100. The reason is that a stringent abatement policy slows down economic growth resulting in less energy R&D in the late period. Both RE and RB achieve the highest values when the backstop energy replaces fossil fuels. After the switch point, RE and RB go down flatly.

5.2 The Trajectory of the Emissions Abatement Policy

This subsection examines the emissions control rates given various abatement policies and R&D policies. The emission control rate is calculated by the formula $-\left(E_t^{AbtPolicy} - E_t^{BAU}\right) / E_t^{BAU}$. It measures the relative change of CO_2 emissions given the abatement policy compared to the BAU

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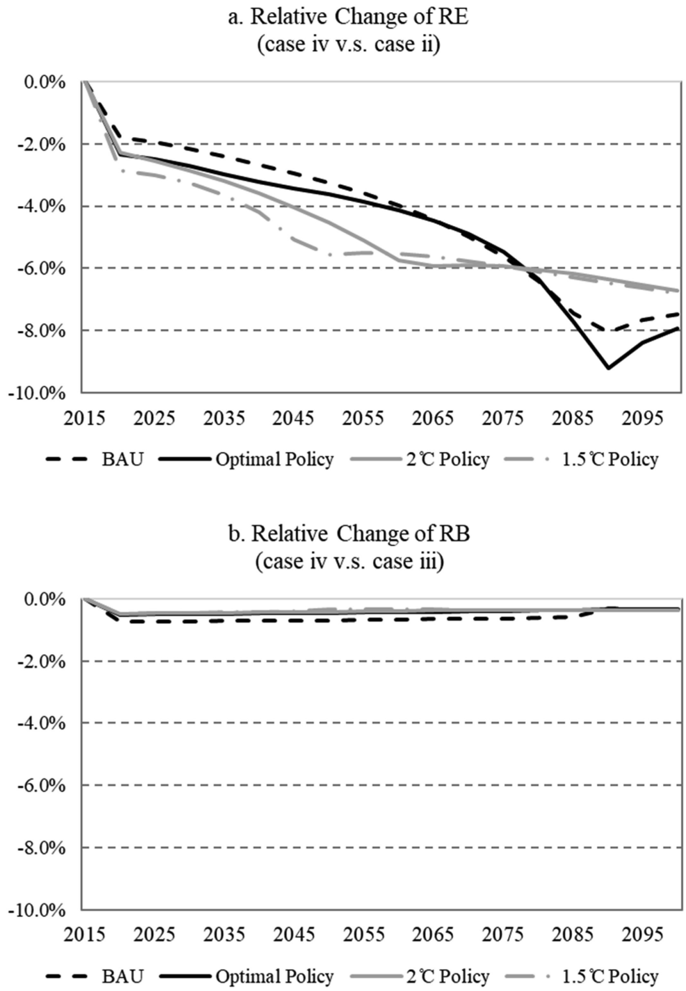
Figure 4: Relative Change of RE and RB from 2015 to 2100



Shown here are (a) relative change of R&D in energy efficiency (case iv with RE & RB v.s. case ii with RE only), which is (RE in case iv – RE in case ii)/RE in case ii (b) relative change of R&D in backstop technology (case iv with RB v.s. case iii with RB only), which is (RB in case iv – RB in case iii)/RB in case iii.

case. The results indicate that the R&D policies have little impact on the abatement policy.[7] Thus, the following discussion focuses on the emissions control rates in a representative R&D case iv (with both RE and RB).

Figure 6 presents the emissions control rates under three abatement policies by 2090. The control rates under the optimal policy start from 12.69% in 2020 and then keep increasing to 37.31% by 2085. The control rates under the 2 °C policy (or the 1.5 °C policy) are about twice (or three times) of those under the optimal policy. The control rate under the 2 °C policy (or the 1.5 °C policy) reaches 100% in 2070 (or 2055) correspondingly indicating that the backstop technology fully replaces fossil fuels by that time. Zero emissions are achieved in 2070 under the 2 °C policy, and in 2055 under the 1.5 °C policy, which is in line with mitigation pathways compatible with 1.5°C

7. The relative change of the control rate is less than 3.50%, 8.90%, and 3.05% given various R&D policies under the optimal abatement policy, the 2 °C policy, and the 1.5 °C policy.

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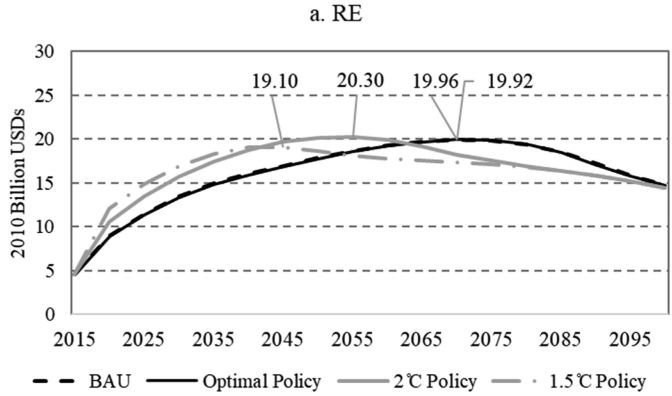
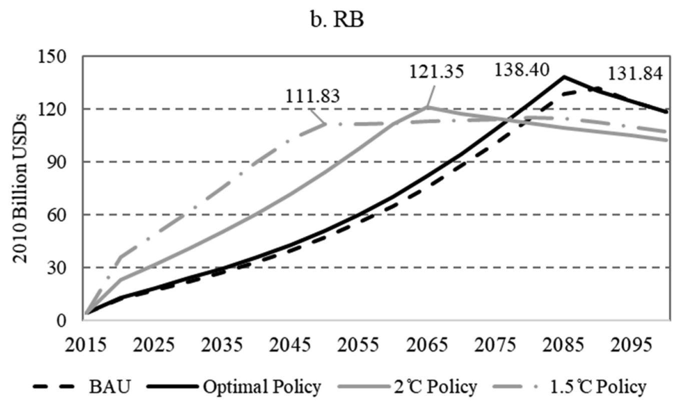
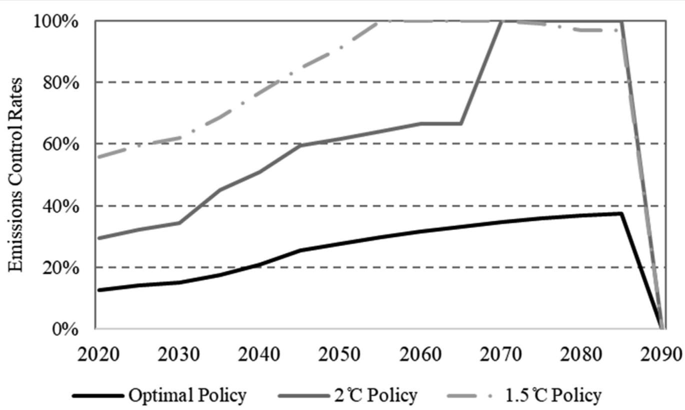
Figure 5: Trajectory of RE and RB in case iv with both RE and RB from 2015 to 2100





Shown here are (a) the amount of R&D in energy efficiency, (b) the amount of R&D in backstop technology.

Figure 6: Emissions Control Rates



Shown is the CO_2 control rate under three abatement policies in case iv with RE and RB.

reported by IPCC (2018). The emissions control rates become zero from 2090 onwards because the energy transition from fossil fuels to a backstop technology occurs in 2090 in the BAU case. Zero emissions are achieved in 2090 even without any abatement policies.

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5.3 Energy Substitution, Economic Gains, Abatement Costs and Impacts on Climate

5.3.1 Energy Substitution

The key rule of energy substitution is the Ricardian comparative advantage theory. Each sector chooses the resource that has a comparative advantage, i.e., the fuel with the lowest energy costs (including extraction costs, conversion costs, the scarcity rent, and the carbon rent). This model assumes a linear substitution among different resources. It explores the impact of abatement policies and the R&D investment policies on energy transition. Table 2 shows the sequence of energy use and the time of energy transition in the capital-goods production sector and the consumption-goods production sector under various abatement policies and R&D investment policies.

The results show that the abatement policy is a key factor that greatly influences the energy transition. Given the BAU policy and the optimal abatement policy, the sequence of energy usage is oil, coal, and backstop technology in the capital-goods production sector, while the sequence is gas, oil, coal, and backstop technology in the consumption-goods production sector. The backstop technology replacing fossil fuels occurs in 2090 in the capital-goods production sector, while it happens in 2095 in the consumption-goods production sector. Given the 2 °C policy, the energy sequence is the same as the ones under the BAU policy and under the optimal policy. However, the switching time from fossil fuels to the backstop technology comes earlier in 2065 in the capital-goods production sector, and in 2070 in the consumption-goods sector. Given the 1.5 °C policy, the energy usage transits from oil directly to the backstop technology in 2045 in the capital-goods production sector, and from gas directly to the backstop technology in 2050 in the consumption-goods production sector. The abatement policy effectively influences the sequence of energy usage and the timeframe of the energy transition. A restrictive abatement policy induces the backstop energy adopted earlier.

Energy R&D investments also affect the energy transition but not as significant as the abatement policy. RE does not change energy transition. Thus, we only present the comparison with RB and without RB in Table 2. The results suggest that RB speeds up the transition from fossil fuels to backstop technology by five years given the BAU policy and the optimal policy. Given a strin-

Table 2: The Sequence of Energy Use and the Time of Energy Transition*

Transition Time	Capital-goods Production Sector		Consumption-goods Production Sector		
BAU	1(Oil to Coal)	2(Coal to BackstopTech)	1(Gas to Oil)	2(Oil to Coal)	3(Coal to Backstop Tech)
w/o RB	2040	2090	2035	2045	2095
with RB	2040	2090	2035	2045	2090
Optimal Policy	1(Oil to Coal)	2(Coal to BackstopTech)	1(Gas to Oil)	2(Oil to Coal)	3(Coal to Backstop Tech)
w/o RB	2040	2090	2035	2045	2095
with RB	2040	2090	2035	2045	2090
2 °C Policy	1(Oil to Coal)	2(Coal to BackstopTech)	1(Gas to Oil)	2(Oil to Coal)	3(Coal to Backstop Tech)
w/o RB	2050	2065	2040	2055	2070
with RB	2050	2065	2040	2055	2070
1.5 °C Policy	1(Oil to BackstopTech)		1(Gas to BackstopTech)		
w/o RB	2045		2055		
with RB	2045		2050		

*The energy-transition time is the starting year when one energy substitutes the other energy. It is not the year when one energy fully replaces the other energy.

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gent abatement policy, the energy transition is much likely to be affected by the abatement policy rather than the R&D investments. The results conclude that the emissions policy is the key factor to accelerate the energy transition, while the R&D investments in backstop technology assist to speed up the energy transition but in a relatively small sense.

5.3.2 Economic Gains

This study examines the economic gains induced by energy R&D investments and abatement policies. We choose consumption gains and GDP gains as two representative indicators. The consumption gains measure the difference in consumption between a specific abatement policy and a BAU policy. It quantifies the utility improvement acquired by households. GDP gains measure the difference in the output between a specific abatement policy and a BAU policy. It reflects the improvement of economic growth. This subsection first examines the impact of abatement policy on the two indicators, then looks into details of the results in the short-term from 2015 to 2050. The short-term discussion gives a reference to the policymakers whose concern is the near-term consequence. Last, it presents the effect of R&D investments on economic gains.

Figure 7 presents consumption gains and GDP gains under three abatement policies. We use case iv (with both RE and RB) as a representative. Only the optimal policy achieves positive gains over the entire time span from 2015 to 2165, while both 2 °C policy and 1.5 °C lead to negative impacts on consumption and GDP. The negative impact under 1.5 °C policy is twice of that under 2 °C policy. We break down the entire time span into three sub-periods. Each period has 50 years. The optimal policy induces positive consumption gains and GDP gains in the three sub-periods. The 2 °C policy and the 1.5 °C policy lead to more loss of economic welfare in the first and second sub-periods but bring more gains of economic welfare in the third period. The economic welfare becomes positive after 2100 in the scenarios of both 2 °C policy and 1.5 °C policy. However, within the 150-year time horizon, the early loss cannot be offset by the late gains in the scenarios of the 2 °C policy and the 1.5 °C policy. These results are in line with Popp (2006).

Next, Figure 8 analyzes the impact of the three abatement policies on economic gains in the short run from 2015 to 2050. We use case iv (with both RE and RB) as a representative. Given the optimal policy, both consumption and GDP are weakly increasing indicating that the optimal policy brings economic gains even in the short run. In contrast, 2 °C policy and 1.5 °C policy lead to economic loss in the short-term. By 2050, the consumption losses are 5.18 trillion USD in the case of 2 °C policy and 17.11 trillion USD in the case of 1.5 °C policy. Comparing Figure 8 (a) and (b), the GDP loss is shared by the consumption loss and investment loss from 2015 to 2040, while the GDP loss is mainly bared by the consumption loss from 2040 to 2050.

Last, Table 3 compares the relative difference of consumption gains and GDP gains between the with RE (or RB) case and the without RE (or RB) case. It measures the impact of energy R&D investments on the consumption gains and GDP gains. We find that RE induces the improvement of consumption and GDP given all abatement policies, although the effect is not strong. Especially, RE results in the same percentage amount of consumption gains and GDP gains meaning that RE does not affect the allocation between consumption goods and investment goods. RB leads to consumption gains and GDP gains in most policy scenarios (expect the occasion in optimal policy/consumption case), also, the effect is significant. RB has a strong positive impact on GDP gains. RB brings more investment improvement rather than consumption gains in the optimal-policy case. However, RB does not change the allocation between the investment goods and consumption goods under 2 °C policy or 1.5 °C policy.

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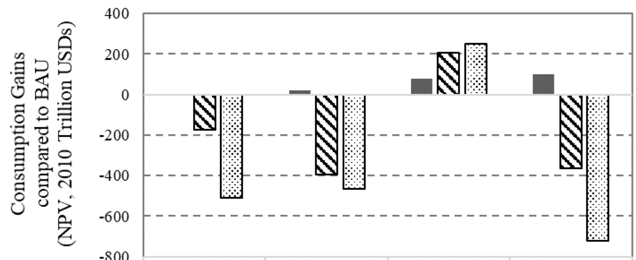
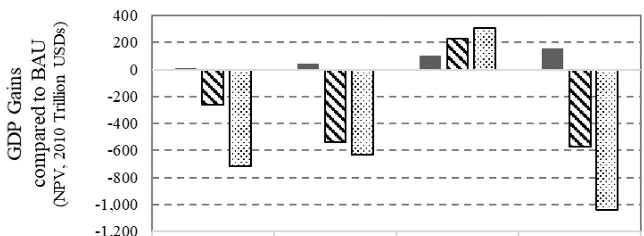
Figure 7: Economic Gains given Three Abatement Policies



	2015-2065	2065-2115	2115-2165	Overall
Optimal Policy	3.3	21.2	77.1	101.6
2℃ Policy	-175.6	-394.8	208.1	-362.3
1.5℃ Policy	-510.2	-464.9	252.4	-722.7

(a) Consumption Gains



	2015-2065	2065-2115	2115-2165	Overall
Optimal Policy	10.5	44.4	103.1	157.9
2℃ Policy	-262.0	-540.4	230.3	-572.1
1.5℃ Policy	-718.4	-630.6	306.4	-1042.6

(b) GDP Gains

Shown are (a) consumption gains and (b) GDP gains in the net present value, 2010 trillion USDs from 2015 to 2165 in case iv (with RE and RB).

5.3.3 Abatement Costs

This subsection presents the total net present value of abatement costs from 2015 to 2115[8] in Figure 9. We discuss the cumulative value of two sub-periods in parallel with Figure 7. The optimal policy has the lowest abatement cost, while a more restrictive abatement policy leads to a higher abatement cost. The abatement cost under the 2 °C policy (or 1.5 °C policy) is ten (or twenty) times of that under the optimal policy. As the backstop technology completely replaces fossil fuels by 2060 in the 1.5 °C policy, the abatement cost in 2015–2065 is much higher than that in 2065–2115. However, in a less stringent policy (e.g., 2 °C policy), the energy transition comes in 2075 resulting in a higher abatement cost in 2065–2155 rather than that in 2015–2065.

Figure 10 presents the dollars per ton of CO_2 emissions reduction. We use case iv (with both RE and RB) as a representative. The cost of per-ton emissions reduction keeps climbing in both

8. As the backstop technology completely replaces fossil fuels in 2095 in the BAU policy, the emissions control rate becomes zero. We only focus on the abatement cost within the upcoming 100 years.

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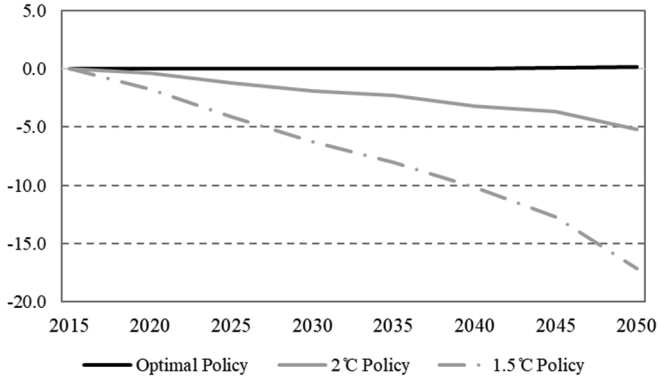
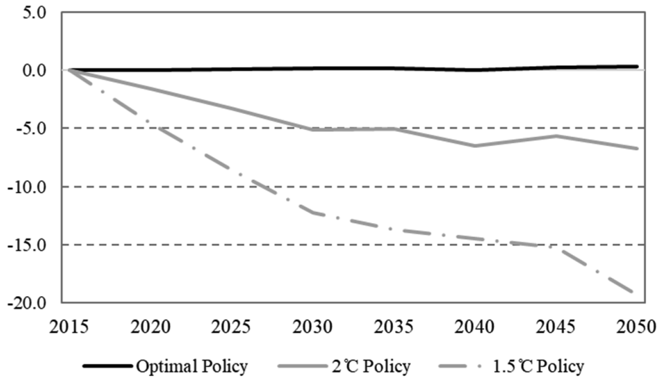
Figure 8: Economic Gains given Three Abatement Policies in the Short-term



(a) Consumption Gains



(b) GDP Gains

Shown are (a) consumption gains and (b) GDP gains in the net present value, 2010 trillion USDs from 2015 to 2050 in case iv (with both RE and RB).

Table 3: Relative Percentage Change of Economic Gains (with RE v.s. without RE; with RB v.s. without RB)

2015–2165	Consumption Gains	GDP Gains
	Optimal Policy	
w RE vs w/o RE	0.09%	0.09%
w RB vs w/o RB	–5.89%	8.28%
	2 °C Policy	
w RE vs w/o RE	0.30%	0.23%
w RB vs w/o RB	10.97%	10.34%
	1.5 °C Policy	
w RE vs w/o RE	0.21%	0.15%
w RB vs w/o RB	9.15%	9.57%

optimal policy and 2 °C policy. In 1.5 °C policy, the cost of per-ton emissions reduction is relatively steady around 330 dollars over the time span before the energy transition to a backstop technology. The cost of per-ton emissions reduction in 2 °C policy is three times of that in the optimal policy.

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Figure 9: Abatement Cost in Net Present Value of 2010 Tri. USD in 2015–2065, 2065–2115, the overall period 2015–2115 in case iv (with RE and RB)

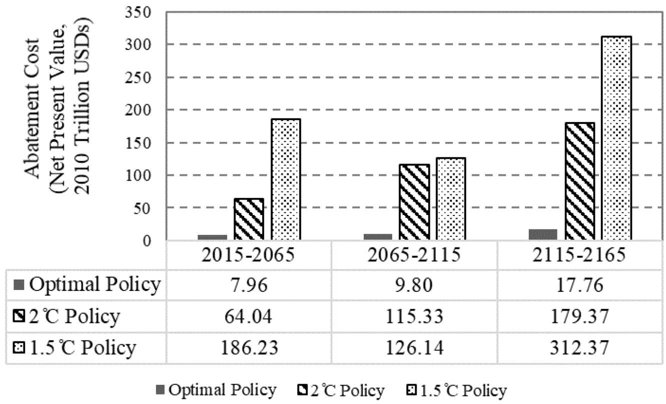
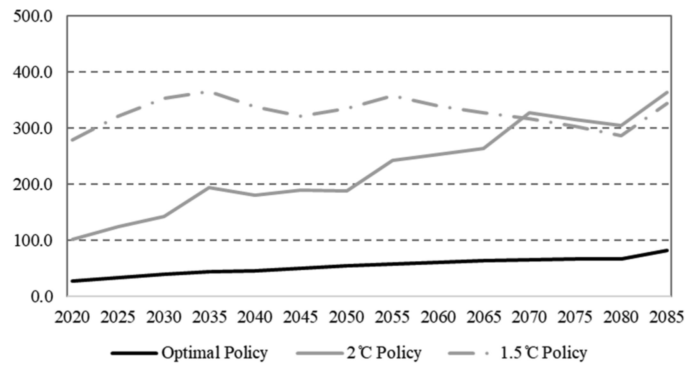


Figure 10: Dollars/Ton of CO_2 reduction from 2020 to 2090



Over the years, the difference in the cost between the 2 °C policy and the optimal policy tends to be large. By 2090, the cost of per-ton emissions reduction in 2 °C policy becomes four times of that in the optimal policy. The cost of per-ton emissions reduction in 1.5 °C policy is ten times of that in optimal policy in 2020 and declines to five times of that in optimal policy by 2090.

Table 4 presents the relative difference in abatement cost between the case with RE (or RB) and the case without RE (or RB). It quantifies the impact of energy R&D investments on the abatement cost. In a more restrictive abatement policy (e.g., 1.5 °C policy), RB is effective to reduce the abatement cost, while in a less restrictive abatement policy (e.g., the optimal policy), RE is useful to reduce the abatement cost. It implies that RB effectively facilitates to cut down the abatement cost in a more stringent abatement policy.

Table 4: Relative Percentage Change of Abatement Cost (with RE v.s. without RE; with RB v.s. without RB)

Abatement Cost	Optimal Policy	2 °C Policy	1.5 °C Policy
w RE vs w/o RE	–0.03%	0.08%	0.07%
w RB vs w/o RB	2.88%	–5.16%	–4.02%

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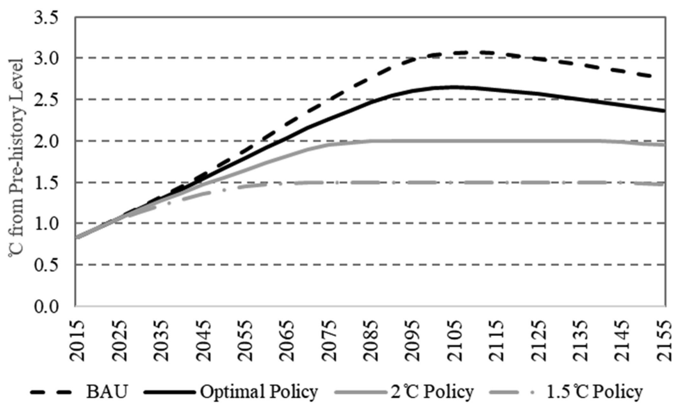
5.3.4 Impacts on Climate

This subsection focus on the impact of the abatement policy on the atmospheric temperature. The energy R&D investments have little effect (<1.00%) in climate change. Thus, we do not discuss it in detail. Figure 11 shows the changes in atmosphere temperature compared to the pre-industry level across four abatement policies. The highest atmospheric temperature reaches 3.07 °C in 2110 under the BAU policy, or 2.65 °C in 2105 under the optimal policy. After the highest point, the temperature goes down slowly due to the energy transition from fossil fuels to a backstop technology. By the end of 2155, the temperature becomes 2.76 °C under the BAU policy, or 2.37 °C under the optimal policy. The atmospheric temperature gets close to the restrictive boundary in 2090 given 2 °C policy and in 2075 given 1.5 °C policy. Afterward, the temperature approaches the restrictive boundary under both 2 °C policy and 1.5 °C policy. Figure 11 indicates that CO_2 emissions have a lag effect on climate change. It can be seen that the atmospheric temperature does not decrease right after the backstop technology replaces fossil fuels. It takes time to achieve the desired level of decrease in the temperature even though the energy transition has already completed.

Figure 11: Atmospheric Temperature (°C) from the Pre-history Level under four abatement policies



6. SENSITIVITY ANALYSIS

6.1 Learning Rate

A key parameter in the model is the learning rate of backstop technology. In the benchmark model, the learning rate is 25%, which is a middle level in the existing literature. According to Jamasb and Kohler (2007) and Kahouli-Brahmi (2008), the learning rate varies among different backstop technology from around 1% to almost 45%. For example, the cost reduction rate of generating off-shore wind energy is 52% by 2050, while the cost reduction rate of generating on-shore wind energy is 26% by 2050 (IEA, 2015). This section tests the sensitivity for a low learning rate that is 13% and for a high learning rate that is 45%. The R&D investments with a high learning rate are twice that with a base learning rate, while the R&D investments with a low learning rate are half of that with a base learning rate. The crowd-out effect quantifies how much RE is ruled out by RB in case iv (with RE and RB) compared to case ii (with RE only). The crowd-out effect is significant in the case with a high learning rate meaning that high learning progress leads to more investments

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in RB and fewer investments in RE. The consumption gains are much higher in the case with a high learning rate. A high learning rate also brings an early energy transition from fossil fuels to backstop technology. The highest temperature and the time of achieving the highest temperature are relatively robust across different learning rates.

Table 5: Sensitivity Analysis for Learning Rate. The net present value of the cumulative results from 2015 to 2115.

Unit: Net Present Value of 2010 Trillion USD	Total R&D	RB	Crowd-out Effect	Consumption Gains	Abatement Costs	Energy Transition Year (to BTech)	Highest Temperature (°C)	Highest Temperature Year
				Learning Rate = 13%				
BAU	6.36	4.46	0.0478	-	-	2095	3.0680	2110
Optimal Policy	6.38	4.48	0.0479	109.15	17.66	2095	2.6503	2105
2 °C Policy	6.66	4.74	0.0492	–389.36	165.57	2070	2.0000	2090
1.5 °C Policy	7.13	5.23	0.0497	–763.68	311.78	2055	1.5000	2075
				Learning Rate = 25%				
BAU	11.57	9.73	0.1038	-	-	2090	3.0692	2110
Optimal Policy	11.91	10.07	0.1098	101.64	17.76	2090	2.6456	2105
2 °C Policy	12.16	10.30	0.1043	–362.26	166.04	2070	2.0000	2090
1.5 °C Policy	13.21	11.37	0.1074	–722.71	312.37	2050	1.5000	2075
				Learning Rate = 45%				
BAU	24.46	22.74	0.2319	-	-	2090	3.0776	2105
Optimal Policy	24.55	22.83	0.2328	119.73	17.78	2090	2.6496	2105
2 °C Policy	25.68	23.93	0.2285	–312.31	171.76	2065	2.0000	2090
1.5 °C Policy	27.71	25.99	0.2331	–631.92	313.99	2050	1.5000	2075

6.2 Time Horizon

Another argument of the model is how long the time horizon should be set. The engineering approach leans towards testing the policy in the short-term horizon because the technology is unlikely to be predicted in the long-term horizon. However, the economic approach tends to examine the policy in the long-term horizon as CO_2 residing in the atmosphere causes the environmental effects in the long term. This subsection examines the sensitivity given a short-term horizon that is 100-year and a long-term horizon that is 300-year. Table 6 presents the relative changes in R&D, consumption gains, GDP gains, and the abatement costs from 2015 to 2100, which indicates the relative changes are small given different time horizons. The overall results are robust for the economic indicators by 2100. For the timing of the energy transition, the 100-year time horizon and 300-year time horizon result in an early energy transition from fossil fuels to backstop technology by five years.

7. CONCLUSION AND DISCUSSION

The simulations of the ENER model present four key findings that are different from the key messages of the existing studies. First, this study finds that the roles of two types of energy R&D investments are different in the impacts on energy substitution and economic welfare. The energy R&D investments in energy efficiency improve the energy services used in production given the amount of primary energy. The key role of energy R&D investments in energy efficiency is to reduce the abatement costs induced by the emissions abatement policy. Different from the energy

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Table 6: Relative Change of R&D, Consumption Gains, GDP gains, Abatement Costs and the Time of Energy Transition over the time span from 2015 to 2100. 100-year time horizon v.s. 150-year time horizon; 300-year time horizon v.s. 150-year time horizon.

Relative Change (NPV of 2010 Tril USDs)	R&D	C gains	Y gains	Abatement Cost	Time of Energy Transition
	100-year v.s. 150-year				
	Optimal Policy				
i. No R&D	0.00	–1.22	1.94	–9.85	0
ii. with RE	–0.53	–1.38	2.11	–9.84	0
iii. with RB	–3.35	1.24	–0.89	–1.74	5
	2 °C Policy				
i. No R&D	0.00	–14.96	–4.17	–2.32	0
ii. with RE	–0.49	–14.99	–4.18	–2.28	0
iii. with RB	–3.23	–12.72	–7.51	–2.84	0
	1.5 °C Policy				
i. No R&D	0.00	–10.64	1.99	–4.35	0
ii. with RE	–0.47	–10.67	2.03	–4.32	0
iii. with RB	–3.20	–8.96	–2.38	12.26	5
	300-year v.s. 150-year				
	Optimal Policy				
i. No R&D	0.00	–0.49	–0.09	0.28	0
ii. with RE	0.22	–0.48	–0.08	0.28	0
iii. with RB	1.76	0.29	0.07	1.32	5
	2 °C Policy				
i. No R&D	0.00	0.52	0.46	–4.59	0
ii. with RE	0.20	0.52	0.45	–4.55	0
iii. with RB	1.73	1.90	–0.03	6.09	0
	1.5 °C Policy				
i. No R&D	0.00	0.50	0.45	–4.69	0
ii. with RE	0.19	0.52	0.44	–4.64	0
iii. with RB	1.67	1.92	–0.04	10.87	5

R&D investments in energy efficiency, the energy R&D investments in backstop technology lower the costs of using backstop technology and further boost the substitution between fossil fuels and backstop energy. R&D in backstop technology bares an 80% share in the total energy R&D investments. We investigate the interaction between two types of R&D. R&D in backstop technology crowds out more R&D in energy efficiency given a more stringent abatement policy, while the R&D in energy efficiency does not crowd out R&D in backstop technology largely. We also examine the interaction of the R&D policy and the abatement policy. A more restrictive abatement policy boosts the R&D investments in the early period from 2015 to 2050. The energy transition from fossil fuels to backstop technologies is speeded up by five years when R&D investments in backstop technologies taken into account. More fossil fuels are used in earlier years in the case with the energy R&D investments in backstop technology than the case without the energy R&D investments in backstop technology, which leads to a higher temperature in the case with the R&D investments in the backstop technology.

Second, this study investigates the resource substitution that is affected by energy R&D investments. The results conform to what the Ricardian comparative advantage theory posits, i.e., each sector chooses the fuel with the lowest cost in the current period. Following this rule, the en-

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ergy sequence in the capital-goods production sector is oil products, coal products, and backstop technology, while that in the consumption-goods production sector is natural gas, oil products, coal products, and backstop technology, given the BAU policy, the optimal policy, and the 2 °C policy. However, provided the 1.5 °C policy, energy use jumps from oil products directly to the backstop technology in the capital-goods production sector, and from natural gas directly to the backstop technology in the consumption-goods production sector. The energy transition from fossil fuels to backstop technology happens in 2090 given the BAU policy and the optimal policy, in 2070 given 2 °C policy, and in 2050 given 1.5 °C policy considering R&D investments. R&D investments in backstop technology boost the energy transition by five years compared to the case without R&D investments in backstop technology.

Third, this study estimates the economic gains and emissions abatement costs across different policies using the models with and without R&D investments. The entire time span is divided into three equivalent parts, i.e., from 2015 to 2065, from 2065 to 2115, and from 2115 to 2165 for a detailed analysis. The improvement of the net present values (NPVs) of output and consumption is not significant in the first two sub-periods (2015–2105), but the NPVs of output and consumption are greatly enhanced by the emissions abatement policy in the last sub-period (2115–2165). The results also indicate that a restrictive policy hurts the economic welfare more in the short run, as well as, benefits the economic welfare more in the long run compared to a less restrictive policy. The abatement costs in the optimal policy are one-tenth of those in the 2 °C policy and one-fifteenth of those in the 1.5 °C policy. R&D in backstop technology leads to about 10% GDP gains given three abatement policies and reduces the abatement costs by 5% in the 2 °C policy and by 4% in the 1.5 °C policy.

Fourth, this study explores the impact of energy-related CO_2 emissions on the atmospheric temperature. The atmospheric temperature climbs up to the highest growth rate from 2090 to 2115 in the BAU policy and in the optimal policy. The reason is that the backstop technology starts to replace fossil fuels. In the BAU scenario, the highest atmospheric temperature reaches 3.07 °C in 2110, while in the optimal scenario, the highest atmospheric temperature reaches 2.65 °C in 2105. In the 2 °C policy scenario, the atmospheric temperature achieves the 2 °C limit in 2090, while in the 1.5 °C policy scenario, the atmospheric temperature gets to the 1.5 °C limit in 2075.

We acknowledge several limitations in our paper. First, we assume the government does not provide subsidies to backstop technology. The energy transition evolves over the years by itself. However, the time of energy transition is affected by some regional specific factors, such as government subsidy and additional environmental policies in a specific region. The switching time varies across different regions. Our paper considers a global energy transition without taking the regional specific issues into account. Second, this study assumes the available resource stock remains constant. However, the available resource stock will change as resource extraction technologies can improve. The formulaic change is out of the scope of this study. It would be more careful about the fact that there would be dramatical changes, especially for the extraction technologies.

ACKNOWLEDGMENTS

We thank Professor Adonis Yatchew, the editor of *The Energy Journal* for his insightful comments, one anonymous referee for suggesting adding another abatement policy scenario (1.5 °C policy) and another anonymous referee for suggesting us to test the robustness given different learning rates of backstop technology. All errors remain ours.

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