AN ANALYSIS ON HYPOTHETICAL SHOCKS REPRESENTING COOLING WATER SHORTAGE USING A COMPUTABLE GENERAL EQUILIBRIUM MODEL

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Due to global warming, it is concerned that cooling water for thermoelectric generation would be run short more frequently in many places of the world. We used a Computable General Equilibrium (CGE) model to quantify the socio-economic impact of a hypothetical shock of capital productivity, which represents shortage of cooling water on thermal power generation plants. The result showed that the magnitude of electricity generation change and subsequent economic indicators change due to 1% capital productivity reduction were varied by region. The mean electricity generation loss was largest in Southeast Asia and smallest in North Africa when an identical shock was given to all regions throughout the simulation period. Considerable regional differences in GDP and electricity price were attributed to not only the capital productivity, but also the amount of capital in thermoelectric sector and its contribution for GDP. Additionally, thermoelectric sector shock propagates into the global economy. These finding demonstrate the significance in quantifying the economic consequence of cooling water shortage.

Key Words: cooling water shortage, thermoelectric sectors, capital productivity, CGE model

1. INTRODUCTION

Fresh water is indispensable to sustain humans’ lives and society. Among various use of water, power plant cooling is one of major water usages in the world. Globally 19.9 EJ/yr of electricity is produced¹. Among various technology, 16.5 EJ/yr (81%) was generated by thermal power in 2010¹. Here the primary energy sources of thermal power includes gas, oil, coal, nuclear, and biomass. The major source of cooling water is seawater for the plants located near seashore and fresh water for those in inland. For example, in USA, 222 km³/yr of surface and ground water was withdrawn in 2010 for cooling water, which accounts for 45% of the national total withdrawal². Availability of cooling water is crucially important in electricity generation. Indeed, shortage in river water and increase in its water temperature influenced the operation of plants. In 2007, nuclear...
and coal-fired plants in the Tennessee Valley Authority system were forced to shut down or curtail operations because intake water exceeded 90 F (32.2°C) for 24 hours. In 2003, France lost the electricity production of 7% to 15% of nuclear capacity (i.e. stopped several reactors) for 5 weeks. Climate change is projected to alter the hydrological cycle globally resulting in more frequent droughts. Hence a comprehensive assessment on the availability of cooling water and its potential impacts to the society is urgently needed by the society.

A number of papers have been published to assess the availability of cooling water and its potential socio-economic impacts. The research topic has been of interest for energy-economists for a long time. Koch and Vögele developed a dynamic economic model incorporating a function for economic evaluation for water shortage and analyzed globally water demand, water availability, and adaptation strategies of power plants to global change. Physically detailed studies based on hydrological models have been carried out by a Dutch research group. van Vliet et al. estimated the reduction of thermal power generation due to decrease in the availability of cooling water in Europe and US. They used a global hydrological model that enabled them to estimate not only river discharge but also river water temperature. Then they incorporated a price-demand function and assessed the climate change impacts on electricity prices. Recently they estimated the future change in global hydropower and thermal power cooling water capacity under the Representative Concentration Pathways scenarios (hereafter RCPs; using multiple global climate models).

Although some detailed physically-based projections of future availability of cooling water are available, economic impacts caused by shortage of cooling water (i.e. the suspension of thermal power production) is still largely lacking particularly at the global scale. Indeed, the methodology is not well established how to represent cooling water shortage in the framework of economic models. Here we investigated to address two research questions. What is the socio-economic consequence of giving a certain intensity of shock representing the shortage of cooling water in thermal power sectors under the framework of a computable general equilibrium model? Whether it spatially propagates into the global economy?

In order to answer these two questions, we used the AIM Computable General Equilibrium model (hereafter AIM/CGE) to analyze the economic consequence of a hypothetical capital productivity reduction shock which represents a shortage of cooling water on thermal power generation plants.

### Table 1 Regional classification.

<table>
<thead>
<tr>
<th>Region</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>Turkey</td>
</tr>
<tr>
<td>China</td>
<td>Canada</td>
</tr>
<tr>
<td>India</td>
<td>United States</td>
</tr>
<tr>
<td>Southeast Asia</td>
<td>Brazil</td>
</tr>
<tr>
<td>Rest of Asia</td>
<td>Oceania</td>
</tr>
<tr>
<td>Rest of Europe</td>
<td>EU25</td>
</tr>
</tbody>
</table>

### Table 2 Classification of thermal and non-thermal electricity.

<table>
<thead>
<tr>
<th>Thermal electricity (Needs cooling)</th>
<th>Non-thermal (Needs no cooling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>Hydro</td>
</tr>
<tr>
<td>Oil</td>
<td>Solar</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Wind</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Other</td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
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</tbody>
</table>

### Table 3 Scenarios design.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Without any shock in any region and year</td>
</tr>
<tr>
<td>ARAY</td>
<td>Shocks for All Regions and Years</td>
</tr>
<tr>
<td>SRAY</td>
<td>Shocks for all Years but USA only</td>
</tr>
</tbody>
</table>

2. METHODOLOGY

This study is divided into two steps:

Step one: Sensitive analysis of impact due to cooling water shortage in thermoelectric sector on social economy using AIM/CGE model.

Step two: Calculation of the cooling water availability change driven by climate change using global hydrology model.

In this study, we only focused on steps one. Therefore, the amount of cooling water shortage is a hypothetical number presenting power plant shut down four days/yr.

(1) AIM/CGE model and scenarios

In this study, we used the AIM/CGE model. AIM/CGE deal with 17 regions (Table 1) and 42 industrial sectors in the world. The details of the AIM/CGE model can be found in its model manual.

The structure of electricity production of AIM/CGE is shown in Fig.1. Altogether nine technologies are used to produce electricity (Table 2). The technologies can be divided into thermal electricity which requires cooling water and non-thermal electricity which does not. A Leontief production function is used for each technology. The output of each technology is aggregated into “Electricity”.

I_80
(2) Simulation
Quantifying the amount of cooling water deficit in the future is a highly challenging work since it is influenced by numerous factors (e.g. climate, electricity demand, hydrological regime of rivers, location of plants, technology used, law and regulations). A part of such assessments have been reported as we introduced in the previous section, but all the projections are highly uncertain under a number of strong assumptions.

We used the AIM/CGE simulation results under the socio-economic views of SSP2 as the baseline. To represent the shortage in cooling water, in this study, we use a simple hypothetical scenario that is to reduce the capital productivity of thermal power cooling by 1% (hereafter call it “shock”). The rationale is as follows. In the field of hydrology, shortage of cooling water of thermal power plants is often expressed as “shut down hour”. The AIM/CGE model is a recursive dynamic general equilibrium model calculating at annual intervals. To fill the gap of temporal resolutions, in this study, a hypothetical 4 days/yr shut down in each region was assumed to conduct sensitivity analysis, and it is approximated at 1% (4days/365days) of power plant productivity reduction in one year.

Two scenarios were prepared as shown in Table 3. The ARAY scenario was used to analyze the propagation of impacts across the regions and the SRAY scenario was used to analyze the time of recovery from the shocks. Comparison of ARAY and Baseline enabled us to analyze the regional responses to the uniform shock. Comparison of SRAY and Baseline was used to identify whether the shock given to one region would propagate globally. Comparison of SRAY and ARAY is to analyze the magnitude of interactions.

3. RESULTS AND DISCUSSION
(1) Electricity generation change
The decrease in the thermal electricity production in 2050 are shown in Fig. 2(a). The reduction was less than 1% in all the regions, with considerable regional differences. The most obvious loss in thermal electricity production was observed in Rest of Africa and the minor one in North Africa.

The decrease in the mean electricity generation is shown in Fig. 2(b). Here the mean electricity generation change rate $EG_i$ was defined as follows.


Where $E_i(t)$ is electricity generation in year $t$. $i$ denotes scenario options: ARAY or SRAY. And $Eb(t)$ is Baseline electricity generation in year $t$. In ARAY, reduction was found in all the regions ranging from 0.017% (North Africa) to 0.226% (Southeast Asia). In SRAY, a sensible decrease was observed only in US (marginal increase was observed in some regions).

Fig. 2(c) shows the rate of thermal electricity production to the total in 2005. The rate is high for Middle East (97%), USA (93%), Japan (92%), Southeast Asia (92%), North Africa (92%), EU25 (89%) while low in Brazil (16%), Rest of Europe (40%), Canada (41%) and Rest of South America (58%). However, it is not as expected that the impacts are more significant for the former regions compared with the latter ones.

To reveal the reasons of considerable regional differences by the same shock, further examination was conducted mainly for ARAY scenario shown below.
(2) GDP change

The magnitude of GDP loss is not in accordance with thermal electricity loss in each region (See Fig. 3 and 2(a)). The most obvious GDP loss happened in Former Soviet Union (0.011%) and the minor one in Rest of South America (0.001%), which is totally different from thermal loss shown in Fig. 2(a) and 2(b).

Regional inconsistency between GDP and thermal electricity change could be the utilization of lower cost non-thermal electricity such as hydropower. AIM/CGE assumes that the hydropower plants can be newly installed until its regional capacity reaches to the Economically Exploitable hydropower Capacity (EEC), which is determined by hydro-geological constraints. Due to rapid increase in electricity demand in the 21th century, hydropower reaches EEC in most of the regions in the world\(^{17}\). An important point is that the electricity cost of hydropower is relatively cheaper than that of other non-thermal technologies. It means that the hydropower dominate country could be less sensitive than thermal dominate regions to thermal electricity cooling water shock such as Brazil where the hydropower take almost 70% of total electricity in 2015\(^{18}\).

Some results in GDP and electricity change show tiny difference. However, the primary purpose of this study is to understand how the shock propagates into the socio-economic system. The shock is a hypothetical and not necessarily represent the projected cooling water shortage impact due to climate change. For example, our study is useful to identify the regions less/more sensitive to the same 1% shock in thermal electricity sector.

(3) Sources of electricity and GDP change

The results so far indicate that the reduction in thermal electricity and GDP were less than 1% (Fig. 2(a) and 3). Under the framework of CGE, electricity production is determined by the factor of production including the capital. Fig. 4(a) shows the capital of thermal power sector in 2050 for the ARAY and baseline simulations. It shows that the capital of ARAY is approximately 0.5 greater than the baseline in all the regions. It means that the 1% reduction in capital productivity of ARAY was partly (i.e. by 0.5%) compensated by additional accumulation of capital.

The loss in GDP could be directly explained by the increase in electricity price along with the
Fig. 4 (a) Contribution rate of accumulative capital in electricity sector (ECCAP) to GDP in global 17 regions in Baseline and ARAY in 2050. (Capital price is same in two scenarios). (b) The relationship between electricity production and electricity price. (c) The ration of electricity sector value added (EVA) to the total sector value added (VA) and the GDP change in ARAY in 2050.

electricity generation reduction (see Fig. 4(b)). However, since GDP is decided by the summation of value added of sectors (VA), differences in GDP change are related with the share of electricity sector (EVA/VA). Fig. 4(c) shows the relationship between GDP loss and the VA share of electricity sector. In Former Soviet Union where the electricity sector takes the biggest share of VA among the 17 regions in the world, shows the biggest GDP loss. Oppositely, in Latin America and India, the EVA is smaller than other regions; hence, the GDP loss was marginal.

4. CONCLUSIONS

This study quantified the consequence of the 1% capital productivity reduction shock due to cooling water shortage in thermal electricity sector under the framework of AIM/CGE model. We use GDP and electricity change rate compared with Baseline to identify which region is less or more sensitive to climate change under the same 1% shock. The findings were summarized as follows:

The magnitude of reduction in thermoelectricity generation and GDP is varied by region. 1% capital productivity reduction leads to less than 1% reduction in thermoelectricity generation and GDP. Increased accumulative capital (0.5%) compensate the 1% productive reduction, which mitigate the electricity reduction rate; While the GDP loss less than 1% is mainly attributed to the share of value added from thermoelectricity sectors: the larger generally leads to more GDP loss.

When the shock was only given to one region (USA in the SRAY simulation), the impacts were hardly propagated into other regions. Minor difference was observed between ARAY and SRAY in USA (e.g. the mean electricity loss by 0.146% and
ACKNOWLEDGMENT: This work was supported by the Environment Research and Technology Development Fund (S-14) of the Ministry of the Environment, Japan.

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(Received September 30, 2016)