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Discussion Paper on the Work of the North-East Asia Clean Air Partnership (NEACAP): Integrated Assessment Models (IAMs)[1]

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[1] This paper has been prepared by Professor Shuxiao Wang in collaboration with the NEACAP Secretariat, but information and assessment in the paper are those of the author.

Executive Summary

North-East Asia shares significant weight of the global air pollutant emissions. Regular dialogue, information sharing, comprehensive assessment and monitoring are required to address sub-regional joint air pollutants control strategies. Integrated Assessment Models (IAMs) are widely used in scientific and policy supporting researches for deriving future energy and pollutants emission pathways and analyzing optimal control strategies across different sectors and regions. Therefore, a review of IAM methodologies and their applications in relevant international mechanisms is performed, under the request of NEACAP. Key contents and proposal are summarized below.

IAMs have been widely used in international clean air actions and mechanisms. Several international mechanisms, such as the Convention on Long-Range Transboundary Air Pollution (CLRTAP) in the United Nations Economic Commission for Europe (UNECE), the Asia Pacific Clean Air Partnership (APCAP), Acid Deposition Monitoring Network in East Asia (EANET), and Joint Research Project for Long–range Transboundary Air Pollutants in Northeast Asia (LTP project), were established to address regional or sub-regional air pollution issues. International mechanisms, such as CLRTAP and APCAP, heavily rely on the IAMs to serve as a mechanism for better coordination and collaboration of clean air programs in the region, to provide technical assistance on air quality management, and to support air quality assessments to identify solutions for clean air, while others (such as EANET and LTP project) utilized some modules of IAMs.

IAMs have been utilized at national levels in North-East Asia, but very limited in the sub-region level of North-East Asia. Several modeling tools, such as GAINS, ABaCAS, AIM and IMED, GUIDE, and REACH, were developed to support policy making of air pollution control with consideration of scenario analysis, abatement cost, optimal pathway, health benefits, and policy solutions. Recent research trend is to integrate energy or economic models with chemical transport models, health models and earth system models, to analyze short-term control strategy as well as long-term pathway for both air pollutants and greenhouse gases. Some IAMs have been utilized in some countries in North-East Asia to provide scientific support on cost-effective analysis and design of clean air solutions at national level. However, joint efforts and systematic policy analyses at the sub-regional level are insufficient to enhance the future regional collaboration of air pollution control strategy.

For future work of NEACAP, the Working Group on IAM and Technical Center of NEACAP shall be established, decisions on IAMs used, common scenario pathways, and other institutional arrangements shall be made. IAMs can be used as a scientific and practical tool to help member countries identify cost-effective emission reduction pathways and measures of air pollution and assist the mitigation of air pollutants both at national level and in the sub-region. Information collection from member countries, future emission scenario design, model inter-comparison, analysis on policy implications and results dissimilation require a coordination body and a dedicated center such as the NEACAP Working Group on Integrated Assessment Models (WGIAM) and Technical Center (TCIAMs). It is therefore suggested that WGIAM shall be established in 2020, which is responsible for the collection of clean air information, development of future emission scenarios, evaluate the cost-efficient measures, and propose sub-region and/or national clean air policy recommendations. A Technical Center on IAMs (TCIAM) shall be established with the approval of SPC, to facilitate the IAM research collaborations and provide a platform enhancing the scientific exchange, capacity building and training among partners. It may coordinate consensus on North-East Asia socio-economic pathways, sub-regional trade and collaboration scenarios, status quo and potential policy tools, etc., determine IAM modeling groups to be involved, and ensemble the IAM results for science-based clean air solution.

I. Introduction

North-East Asia often refers to the region including Japan, the Republic of Korea, Democratic People's Republic of Korea, Mongolia, China and the Russian Federation. Air pollutant emissions in North-East Asia share significant weight of the global emissions. International Institute for Applied Systems Analysis (IIASA, Cofala et al, 2012) reported that East Asia shares 36% of global sulfur dioxide (SO2) emission, 29% of global nitrogen oxides (NOx) emission, and 36% of global particulate matter less than or equal to 2.5 µm (PM2.5) emission. Emission Database for Global Atmospheric Research (EDGAR, Crippa et al., 2018) showed that in 2012, North-East Asia shared 33%, 28%, 31% of global SO2, NOx, and PM2.5 emissions, respectively. Similar share of global emissions from North-East Asia was also reported in other inventories such as MIX (Li et al., 2018) and Regional Emission inventory in Asia (REAS) (Kurokawa et al., 2013). In the past few decades, countries such as Japan, China, and the Republic of Korea have been intensifying their efforts for implementing air pollutants abatement measures and have achieved substantial progress on air quality improvement over the last decade. The anthropogenic emissions in North-East Asia exhibit declining trends, particularly for SO2 and PM2.5 which decreased by 15% and 12% from 2005 to 2010 respectively (Wang et al, 2014). China has achieved significant declines of pollutants emissions during 2013-2017, with the implementation of the toughest-ever clean air policy significant declines in PM2.5 concentrations occurred nationwide. Emissions of SO2, NOx and primary PM2.5 were reduced by 16.4, 8.0 and 3.5 Tg, respectively. The estimated national population–weighted annual mean PM2.5 concentrations decreased from 61.8 to 42.0 µg/m3 in 5 years (Zhang et al., 2019). Japan has achieved a high level of air quality, decreased its ambient PM2.5 concentrations by almost 30% during 2000-2016. However, air pollution is still one of the most challenging environmental issues in this region. Less than 8% of the population of Asia and the Pacific enjoyed healthy air – within the World Health Organization (WHO) Guideline – in 2015 (UNEP, 2019). Improving the air quality requires action to further reduce the emissions of multiple air pollutants in the sub-region.

Air pollution does not recognize geographic boundaries. The transboundary nature of air pollution in the sub-region requires effective cooperation to ensure experience exchange, information sharing, comprehensive assessment and monitoring as well as to promote dialogue on potential multilateral measures to tackle the problem. With support from NEASPEC member States, the North-East Asia Clean Air Partnership (NEACAP) was launched during the 22nd Senior Officials Meeting (SOM) in October 2018. The NEACAP would serve as a voluntary framework to address transboundary air pollution in North-East Asia, and act as the key framework in addressing air pollution issues in the subregion. Subsequently, the Science and Policy Committee (SPC) was established upon member

States' nomination of national experts and research institutes as the NEACAP Technical Centers. The First Meeting of NEACAP Science and Policy Committee (SPC-1), which was held on 5 July 2019, considered IAM as one of the core programmes of NEACAP. The meeting agreed to initiate the work on IAM with the approach of multiple models to enhance the credibility of outcomes for reference policy and technical cooperation, and to establish a Working Group on IAMs (WGIAM) to prepare the detail work plan. Against this background, this report aims to review methodologies and studies in North-East Asia and those applied by relevant international mechanisms on air pollution.

II. IAMs in the existing international mechanisms on air pollution

Recognizing the growing need of many countries to address transboundary air pollution and its impacts, different international mechanisms of cooperation were developed. Regional examples include but not limited to the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP), the Asia Pacific Clean Air Partnership (APCAP), Acid Deposition Monitoring Network in East Asia (EANET), and Joint Research Project for Long–range Transboundary Air Pollutants in Northeast Asia (LTP project).

2.1 CLRTAP

A successful example of relevant international mechanisms on air pollution is CLRTAP. It was first signed in 1979, and now it has 51 parties and 8 protocols. The Convention's executive body is the United Nations Economic Commission for Europe (UNECE), with three main subsidiary bodies: the Working Group on Effects, the Steering Body to EMEP, and the Working Group on Strategies and Review. The IAM is charged by EMEP, which consists of four centers: the Chemical Coordinating Centre (CCC), the Meteorological Synthesizing Centre-West (MSC-W), the Meteorological Synthesizing Centre-East (MSC-E) and the Centre for Integrated Assessment Modelling (CIAM). They play different roles in the modeling task. MSC-W develops chemical transport model EMEP MSC-W, and then quantified source-receptor relationships for PM, precursors to ground-level ozone, and acidifying and eutrophying pollutants (Simpson et al., 2012). MSC-E develops models for heavy metals (Travnikov and Ilyin, 2005) and persistent organic pollutants (POPs) (Gusev et al., 2005) which are still under development. CIAM, hosted by IIASA, focuses on integrated source-receptors matrices, which was developed by MSC-W as basic input data to the comprehensive integrate assessment model such as Greenhouse gas–Air pollution Interactions and Synergies (GAINS).

During the negotiation of the 1994 Sulphur Protocol II and the 1999 Gothenburg Protocol under CLRTAP convention, the critical loads approach was introduced, attempting to assign national targets according to environmental vulnerability. Regional Air pollution Information and Simulation model (RAINS) was then used to quantify and optimize the 'gap closure' approach (Schoepp et al., 1999). It supported a differentiated, more cost-effective goals compared to the 1985 Sulphur Protocol I, which regulated at least 30% reduction on annual sulfur emissions among all parties. However, the protocol forming method with IAM was criticized by some scholars. Levy (1995) pointed out that when modelling cost-effective scenarios, the 5% most sensitive areas in each grid of critical loads map were excluded, therefore reduced the total costs. Albin (1995) stated the importance to concern equality, equity and compensatory justice principles to the convention, because of the non-uniformed distribution of environmental benefit and abatement costs. Adam Byrne (2015) argued that the reduction target in the 1994 Sulphur Protocol II became generally weaker because of the concern of costs. What's more, the cost-efficiency and environmental criteria seemed to override other criteria such as national capacity, when assigning reduction goals. For example, according to the model result, Poland need to reduce emissions by 66% to reach its 2010 ceiling, and that would also achieve great cost-efficiency. However, the economy of Poland was weak at that time.

RAINS/GAINS developed by CIAM were used to derive optimized emission reductions strategies for air pollutants (also for greenhouse gases in GAINS), taking into consideration of control measures costs and human health and ecosystem benefits. It supported the work of the Task Force on Integrated Assessment (TFIAM) which brings together information from the Parties, from the EMEP technical centres and from other bodies of the Convention to assess the expected impact of current and future regulations and to identify future priorities and stakes[2].

With the efforts under CLRTAP and support from integrated assessment models, significant ecological and health benefits were observed (Bull et al., 2008). Economically, compared to 1990 emission levels, the reduction scenario results reveal that about 100 billion ECU per year of damage costs have been avoided (Krewitt, 1998). Since its inception 40 years ago, the CLRTAP has achieve unprecedented results and become a successful regional framework for controlling and reducing the damage to human health and the environment caused by transboundary air pollution. The achievements until today are unparalleled. Air pollutant emissions and economic growth have been decoupled. Emissions of certain air pollutants have been reduced by 40 to 80 per cent. Forest soils and lakes have recovered from acidification. 600,000 premature deaths have been avoided annually.

The amended Gothenburg Protocol of the Convention came into force on October 7th, 2019. It established air pollutants emissions reduction goals for 2020 and beyond. Different reduction targets were assigned to different countries, based on the result from GAINS model. The analysis from the Expert Group on Techno-Economic Issues showed great cost-effectiveness of emission reduction target (the costs of control strategies count for less than 0.01% of EU GDP, while the benefit of avoided health and work loss can account for more than 20% of Europe's total GDP). However, a compromise

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[2] Laurence ROUÏL, Review of Regional Air Pollution Control Mechanisms-Focus on the LRTAP Convention, 2016. http://www.neaspec.org/sites/default/files/TAP_%20Annex%20III.%20Review%20of%20Regional%20Air%20Pollution%20Control%20Mechanisms.pdf

was made by leveling down the emission reduction target, to get as many countries as possible on board ratifying the protocol. Future plans include assessment of the amended protocol with GAINS, continuing to improve the estimates of air pollution impacts and control costs, considering relative importance of various sources and additional local and regional control measures, and analyzing the cost-effectiveness of Northern Hemispheric emission reduction strategies for ozone precursors using GAINS[3].

2.2 APCAP

In Asia Pacific, there has been several intergovernmental and voluntary cooperation frameworks and initiatives working on air pollution with varying focus and functions and scope in terms of membership. The Asia Pacific Clean Air Partnership was established in 2015 as a mechanism and platform to promote coordination and collaboration among various clean air initiatives in Asia Pacific. Sixteen countries have joined the APCAP since 2015: Afghanistan, Cambodia, India, Iran, Japan, Republic of Korea, Malaysia, Maldives, Mongolia, Nepal, New Zealand, Pakistan, Philippines, Singapore, Sri Lanka, Thailand. The Partnership supported Mongolia, Sri Lanka and Thailand to conduct air quality and health assessments which were used for evidence-based policy making. Agra and Phnom Penh received support to develop clean air plans.

The Asia Pacific Clean Air Partnership aims to serve as a mechanism for better coordination and collaboration of clean air programs in the region, to provide a platform to generate and share knowledge on air pollution initiatives, policies and technologies in the Asia Pacific region, to strengthen institutional capacity, provide technical assistance on air quality management, and to support air quality assessments to identify solutions for clean air. Over the past few years, much has been achieved in the clean air agenda. The Asia Pacific Clean Air Partnership is now responding to 2017 Resolution 3/8 of the third UN Environment Assembly on ‘Preventing and reducing air pollution to improve air quality globally’. The APCAP Science Panel was established to bring together scientific expertise from the multiple regional initiatives to provide clear policy options based on the best science to support action on air pollution in Asia Pacific. The APCAP Science Panel supported the development of the APCAP 2019 new report, *Air Pollution in Asia and the Pacific: Science-based Solutions*, highlights the need for decisive action, priority measures for reducing health impacts, and in particular identifies 25 priority measures focusing on (a) Regional application of conventional measures; (b) Next-stage air quality measures that are not yet major components of clean air policies, (c) Measures contributing to development priority goals with benefits for air quality.

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[3] UNECE, Decision 2018/5. Long-term strategy for the Convention on Long-range Transboundary Air Pollution for 2020–2030 and beyond. https://www.unece.org/fileadmin/DAM/env/documents/2018/Air/EB/correct_numbering_Decision_2018_5.pdf

The IAM framework was used, combining scenarios from IEA WEO and FAO, with GAINS, Chemical Transport Models, DO3E model and WHO GBD (see figure below)[4].

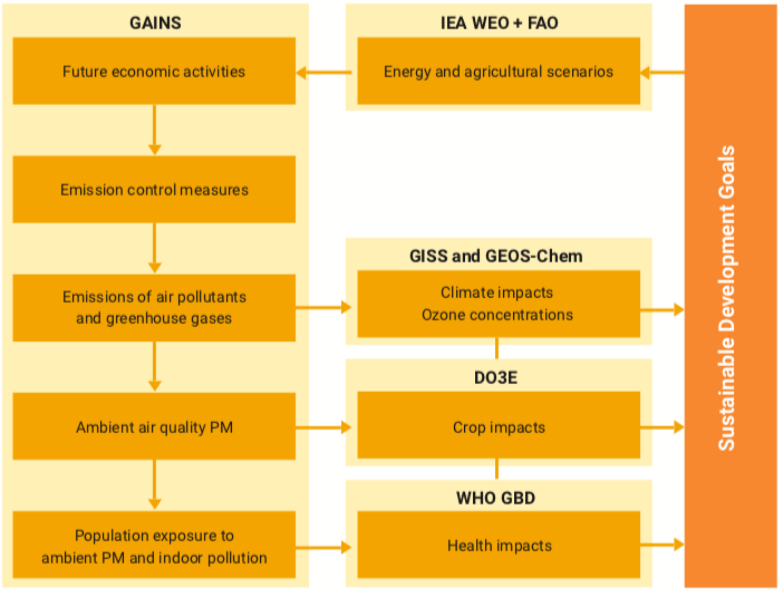

Figure 1. The suite of models used for this analysis and the interactions between models

The APCAP Joint Forum has become the key venue in the Asia Pacific for sharing latest policy-relevant scientific knowledge, and information on the state of national and international efforts. The Joint Forum also aims to identify priority air quality issues, promote regional approaches to combat the priority issues where appropriate and identify appropriate forums and existing mechanisms to help address air pollution challenges of the region.

2.3 EANET

EANET is an intergovernmental regional network established for promoting cooperation among countries in East Asia to address acid deposition problems. The objectives of EANET are (1) to create a common understanding of the state of the acid deposition problems in East Asia, (2) to provide useful inputs for decision making at local, national and regional levels aimed at preventing or reducing adverse impacts on the environment caused by acid deposition, and (3) to contribute to cooperation on the issues related to acid deposition among the participating countries. Now there are 13 participating countries under EANET.

As the institutional framework for EANET, the Intergovernmental Meeting is the decision making a body of EANET. The Scientific Advisory Committee was established under the Intergovernmental Meeting, and the Secretariat and the Network Center were designated to support the network. These

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[4] https://www.ccacoalition.org/en/resources/air-pollution-asia-and-pacific-science-based-solutions-summary-full-report

organizations promote the network activities in close communication, coordination and collaboration with the national focal points, national centers and national QA/QC managers in the participating countries.

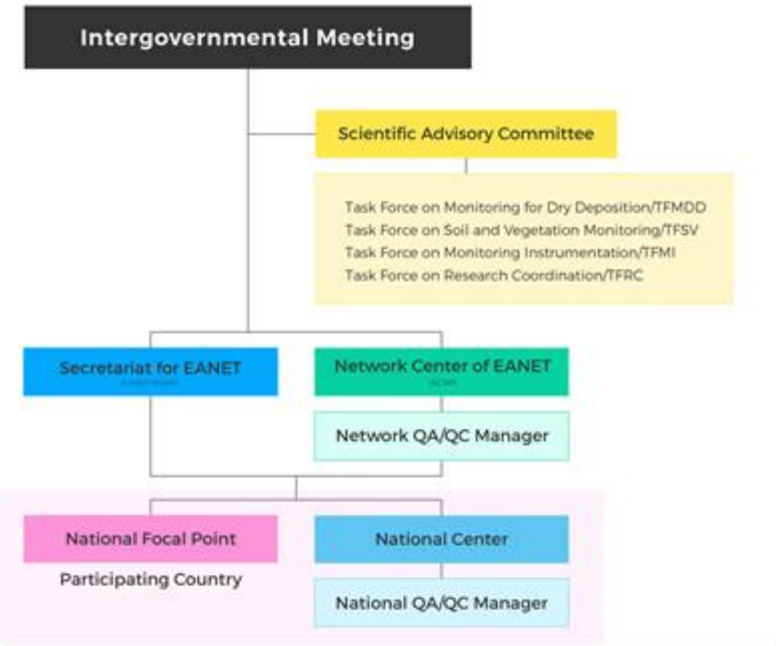

Figure 2. Institutional framework of the EANET

The major activities of EANET include the following aspects: (1) Acid deposition monitoring; (2) Compilation, evaluation, storage and provision of data; (3) Promotion of quality assurance and quality control (QA/QC) activities; (4) Implementation of technical support and capacity building activities; (5) Promotion of research and studies related to acid deposition problems; (6) Promotion of public awareness activities. Recently the Medium-Term Plan which decided relevant efforts to be made under partnership during 2016-2020 is reviewed, the monitoring of acid deposition have been enhanced, and joint relevant researches have been continuously carried out. However, several challenges are also faced by EANET, including deciding the direction and scope of the expansion of EANET, researches on models and future air pollutants emissions need to be improved. Especially, EANET could review available methods and knowledge regarding monitoring/ modeling/emission estimates/effects assessment (e.g., EMEP could be served as one of the models). Engagement with other regional mechanisms and integrated assessment for synergistic solutions are proposed for future work.

2.4 LTP project

In order to establish common understanding of mechanism of transboundary movement of pollutants, Republic of Korea, China and Japan established LTP project in 1996. The objectives of the LTP project are to study the state of air quality, the influence of neighboring countries, and the policy making of each country to improve the air quality. The monitoring sites in the three countries: China, Korea and Japan, were selected under an agreement of the Joint Operating Committee for LTP project to capture transboundary movement of air pollutants in Northeast Asia. What's more, air quality modeling studies were conducted to identify the Source–Receptor (S–R) relationships among three countries, and results from three countries for the base year, 2017, showed that the local emissions dominated the $PM_{2.5}$ concentrations in each major city, including polluted days. The self–contributions in China, Korea and Japan were 91.0%, 51.2%, and 55.4%, respectively. The influences of PM2.5 are mutual among China, Korea and Japan. Further research on species–targeted monitoring and emission reduction will effectively contribute to improve air quality through continuous cooperation among the three countries. Such studies could be included in the IAM framework of NEACAP in the future.

III. IAM methodologies

IAMs was first introduced from economic, systematic and natural science perspectives. These models are appropriate to study social and economic impact of certain environmental problems. Nordhaus et al. (1992a, 1992b, 1996) developed Dynamic Integrated Climate-Economy model (DICE) and Regional Integrated model of Climate and the Economy model (RICE) since 1960s, with a measurement of utility functions and cost functions of climate change. Computable General Equilibrium models (CGE) represent the circular flow of goods and service in an economy, linking environmental emissions with economy, such as Emissions Prediction and Policy Analysis model (EPPA) by MIT (Jacoby, 2006) and Asia-pacific Integrated Model (AIM-CGE) by NIES. Linear programming method is also used in some IAMs, such as MARKet ALlocation (MARKAL/TIMES), which is used to finds the "best" Reference Energy Systems for each time period by selecting the set of options to minimize total system cost over the entire planning horizon (Rafaj et al., 2007; Mohammad et al, 2009).

With the model development, the scope of IAMs extended from energy sector to the wider human-earth interactions. IMAGE model by PBL includes social-economic driver, comprehensive and balanced integration of energy and land systems, the sources and sinks of emissions, natural resources and ecosystem in earth system models (IMAGE documentation[5]). Global Change Assessment Model (GCAM) developed by Joint Global Change Research Institute (JGCRI) includes comprehensive and hierarchical energy system, agriculture and land system with consideration of water resource, greenhouse gas emission and non-GHG air pollutants emissions (Calvin et al., 2019; GCAM documentation[6]). They can be used to study environmental and social benefit and cost of certain policy or future pathway.

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[5] https://models.pbl.nl/image/index.php/

[6] http://www.globalchange.umd.edu/gcam/

Several models and policy tools were developed for air pollution control specifically. They can support policy making with consideration of abatement cost, optimal pathway and policy options, control benefits, etc. Recent research trend is to integrate energy or economic models with chemical transport models, health models and earth system models, to analyze short-term control strategy as well as long-term pathway for both air pollutants and greenhouse gases.

3.1 GAINS model

RAINS model was developed by IIASA under the need of a scientific basis for emissions reductions under CLRTAP, together with Abatement Strategies Assessment Model at Imperial College in London, the Coordinated Abatement Strategy Model at Stockholm Environment Institute (Willemijn et al., 1999). It composed of emission module (emission inventory), abatement cost database, and geographic dispersion model developed for European Monitoring and Evaluation Program (EMEP) to evaluate air pollution transport. RAINS model can either be operated in scenario analysis mode, or optimization mode to determine the least expensive ways of achieving given reductions.

GAINS model made further development from RAINS, adding on six Kyoto greenhouse gases, fuel substitutions and efficiency improvement options. For example, in RAINS the point of technological feasible emission reduction on a single pollutant cost curve was determined by the maximum application of end-of-pipe technologies, but in GAINS further reductions can be achieved by changing the underlying activities, such as switching to another type of fuel with consideration of energy efficiency (IIASA, 2008). Health impact in GAINS is based on the findings of the WHO review on health impacts of air pollution, specifically for fine particulate matter, ground-level ozone and other burdens from indoor pollution. Vegetation production impacts from ground-level ozone are also considered, including four types of crop in Asia, i.e. rice, wheat, maize and soybean. European Union is now using GAINS for compliance evaluation, with the attempt to downscale model to finer resolution and represent short term limit value for air pollutants (Kiesewetter et al., 2014). The long-range transport is calculated based on linear transfer coefficient calculated with EMEP model (Simpson et al., 2012; Amann et al., 2011).

Emission scenarios or inventories are needed as model input. Scenarios are developed using different IAM models, such as PRIMES, WEM, MESSAGE, and so on. The next half of integrate assessment is done by GAINS, including analysis of environmental quality, pollution impacts and control strategies. IEA (2016) special report reviewed the cause of air pollution from energy sector, the future trend and goal, using IEA energy model as well as GAINS model for emission calculation. Regional analysis, including USA, Mexico, EU, China, India, Southeast Asia and Africa, were carried out, demonstrating air pollution from energy sector in details. The report also proposed a clean air scenario using IAM. 1.7 million avoided deaths for outdoor air pollution and 1.6 million for household pollution in 2040 was found.

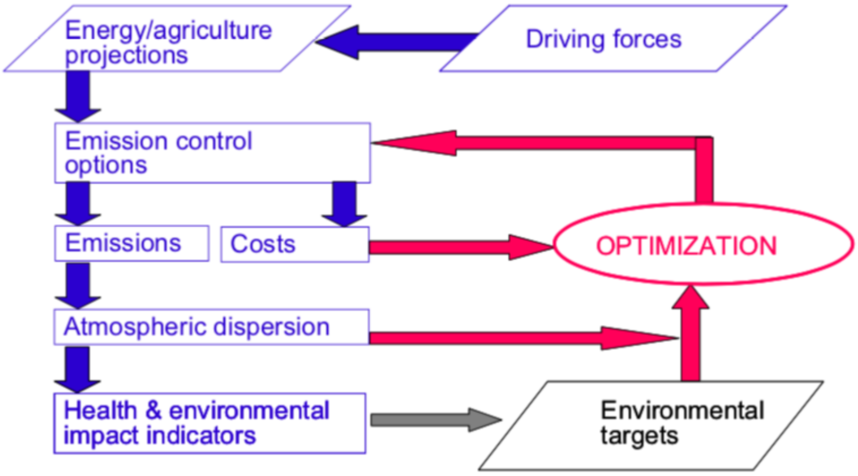

Figure 3. The iterative concept of the GAINS optimization (IIASA, 2008)

Regional GAINS models can support national and sub-regional analysis, including long-range transport air pollutants based on chemistry transport models and derived statistical models (or functions). RAINS-Asia used ATMOS to calculate long-range pollutants transport (Foell et al., 1995). Streets et al. (1999) studied transport of sulfur across North-East Asia and projected future emission and abatement scenario. Cofala et al. (2004) simulated SO_2 cost-effective control measures using RAINS-Asia. Yamashita et al. (2007) evaluated cost-effectiveness of NOx control strategies in Asia, using extended ATMOS-N (NOx module for ATMOS model, Holloway et al., 2002) to identify long-range NOx transport and deriving critical loads and cost functions from RAINS-Asia. Chae et al. (2003) integrated RAINS-Asia with PAGE95, a climate model, to assess cost and benefits of CO_2 and SO_2 control strategies in North-East Asia. In GAINS-Asia, the global-regional chemistry transport model TM5 was used to develop source receptor relationships of aerosol and ozone precursors (IIASA, 2008). The calculations of ambient concentrations of the various pollutants are in 1°×1°spatial resolution. GAINS has been developed into local versions for further analysis. Dong et al. (2015) analyzed air pollution benefit from carbon mitigation with GAINS-China. GAINS-Korea was matched with CAPSS inventory and assessed air quality improvement potentials for Seoul Metropolitan Area (Kim et al., 2016). GAINS-Russia was used to explore the measures and costs of reducing the 2005 air pollution levels by 5 percent by 2020 (Astroem et al., 2013).

3.2 ABaCAS model

The Air Benefit and Cost and Attainment Assessment System (ABaCAS) is a policy-oriented integrated scientific assessment system, which aims to address the key question whether the proposed control strategy and resulting air quality benefit will be cost-efficient (Xing et al., 2017). This system includes several tools: The International Cost Estimate Tool (ICET), which estimates costs associated with certain control strategies based on cost information of control technologies applied in specific emission sectors; The Response Surface Model (RSM), built on meta-simulation scenarios with advanced statistical interpolation techniques, which provides a real-time estimated response of pollution concentrations to emissions changes; The Software of Model Attainment Test (SMAT), merging RSM-predicted and monitor-observed data, which performs attainment tests to examine whether an emission reduction strategy will lower future ambient air pollution concentrations to a certain level; and The Environmental Benefits Mapping and Analysis Program (BenMAP), which estimates monetized human health effects resulting from the change in ambient air pollution, based on the health impact function or the concentration-response function in epidemiology studies and an estimate of the monetized benefit per avoid endpoint. The framework of the model is shown in Figure 3. Recently, the LEast-COst (LE-CO) module was developed and integrated to the ABaCAS system, which provides the optimization of control strategies between RSM and ICET module, based on polynomial function RSM and marginal abatement costs (Xing et al., 2019).

The input of ABaCAS can be emission inventories or monitoring data. For future studies, emission pathways are needed. GCAM is linked (GCAM-ABaCAS) to address future emission pathways. Regional air pollutants transport and joint pollution control strategy are considered in ABaCAS. In RSM model, regional transport of air pollutants is quantified by two major processes: (1) the regional transport of precursors enhancing the chemical formation of secondary $PM_{2.5}$ in the target region; (2) the formation of secondary $PM_{2.5}$ in the source region followed by transport to the target region (Zhao et al., 2017). Alternative source identification methods include back-trajectory method (Wang et al., 2015), embedding chemical tracers in chemical transport models (Li et al., 2015), adjoint analysis, for example, Zhang et al. (2016) used adjoint GEOS-Chem to analyze regional transport contributions during Beijing APEC summit. However, non-linearity and computation efficiency are two concerns for transport model in Integrated Assessment Mode. Thus, ABaCAS integrated RSM as chemical transport module.

After confirming contributions of air pollutants regional transport to local pollutants concentrations, optimal joint control strategy can be addressed by LE-CO. Chang et al (2019) studied transport matrix among the cities in Beijing-Tianjin-Hebei region, regarding cities and regions as both sources and receptors. Xing et al. (2019) studied joint controls on multiple pollutants across the Beijing-Tianjin-Hebei region. The cost of reductions from individual sources in different regions are compared, thus the cost curves with different local and regional emission reduction ratios are constructed. The optimal control strategy can be derived.

With ABaCAS model, extended health benefits can be calculated. Li et al. (2019b) studied health benefit of $PM_{2.5}$ reduction in Pearl River Delta region in China, and it showed 24% decline of the population-weighted average $PM_{2.5}$ concentration over PRD, more than 3800 $PM_{2.5}$-related mortality decrease due to decreases in stroke (48%), ischemic heart disease (35%), chronic obstructive pulmonary disease (10%), and lung cancer (7%). A 13% reduction in $PM_{2.5}$-related premature deaths from these four causes yielded a large economic benefit of about 1300 million US dollars. The benefit can be further compared with previously derived emission control costs among different control scenarios. Future improvement of impact assessment can focus on joint greenhouse gas reduction, vegetation damage alleviation, and social cost of policy.

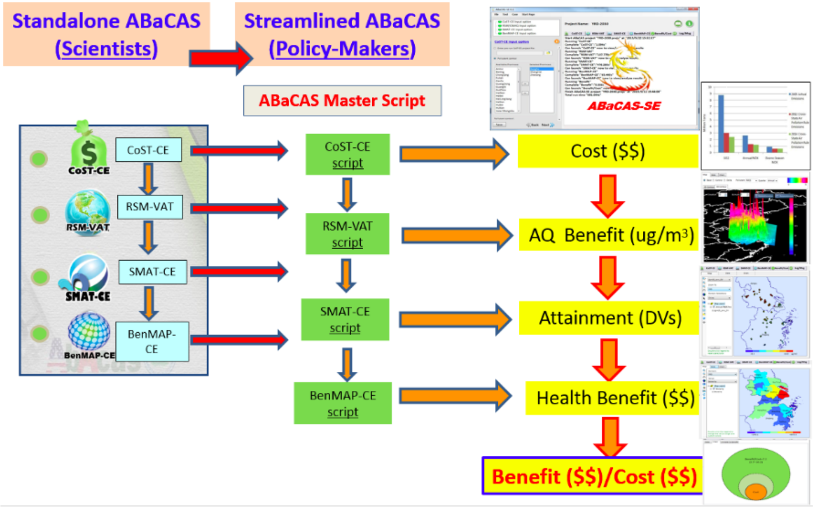

Figure 4. ABaCAS conceptual framework (http://www.abacas-dss.com/)

3.3 REACH model

Regional Emissions Air Quality Climate Health model (REACH) is developed by Institute of Energy, Environment, and Economy, Tsinghua University, in cooperation with Massachusetts Institute of Technology (Zhang et al., 2017b). It composes of the China Regional Energy Model (C-REM), which simulates economic growth, energy use, and emissions pathways for each region; emission inventory module, which can be Multi-resolution emission inventory for China (MEIC, http://www.meicmodel.org or Regional Emission Inventory in Asia (REAS, http://www.nies.go.jp/REAS/); chemical transportation module, which can be WRF-Chem with CMAQ or CEOS-Chem; CREM-Health Effect model (CREM-HE) which use relative risk factors from epidemiological literatures to assess health impact, and further models the economic and social welfare impact by labor hour loss and loss of leisure.

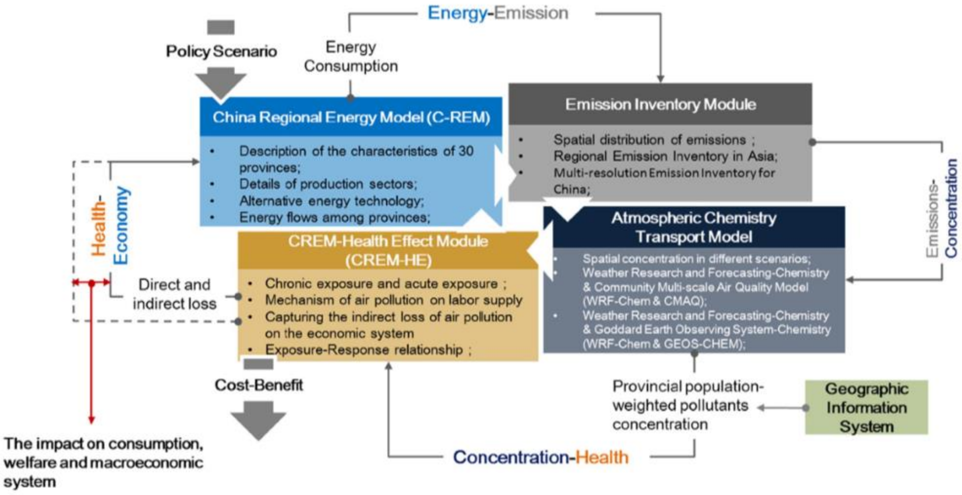

Figure 5. REACH framework (Zhang et al., 2017b)

Using REACH model, several studies are conducted linking transport of air pollution with costs and benefits analysis. Li et al. (2018) studied air quality co-benefits of carbon pricing in China. Transport of air pollutants is considered by using GOES-Chem, but contribution ratio of regional to local emissions leading to health and labor costs was not quantified. In another study by Li et al. (2019b), they found that China's pledge to peak CO_2 emissions before 2030 has the co-benefits from ozone and its transboundary impact for both $PM_{2.5}$ and ozone, therefore 1200 (900–1600), 3500 (2800–4300), and 1900 (1400–2500) premature deaths will be avoided in South Korea, Japan, and the US. GEOS-Chem was used to determine the long-range transport air pollutants effect.

3.4 AIM/CGE and IMED model

AIM/CGE is an integrated general equilibrium model for integrated sectorial activities assessment, with an emphasis on the Asia-Pacific region, developed by National Institutes for Environmental Studies (NIES). Air pollutants module was also developed through a bottom-up approach (Hanaoka et al., 2018). Benefits of air quality improvement from carbon mitigation was assessed in South Korea (Kim et al., 2020).

Extended from AIM/CGE model, Integrated Model of Energy, Environment and Economy for Sustainable Development (IMED) is developed by the Green and Low Carbon Research Group, College of Environmental Sciences and Engineering at Peking University[7]. It consists of IMED|DATA, IMED|MIN (module for data mining, under development), IMED|CGE (general equilibrium model to show policy impact on economy or develop emission pathways, AIM/CGE-China), IMED|HEL (health module to evaluate health loss and related economic loss), and IMED|HIO (develop energy demand from different sectors). Studies evaluated $PM_{2.5}$ pollution-related health impacts (Xie et al., 2016), ozone pollution-related health impacts (Xie et al., 2017) and

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[7] http://scholar.pku.edu.cn/hanchengdai/imed_general

their comparison (Xie et al., 2019) on the national and provincial economy of China, using the concentration data provided by GAINS-China, and emission pathways provided by AIM/CGE-China.

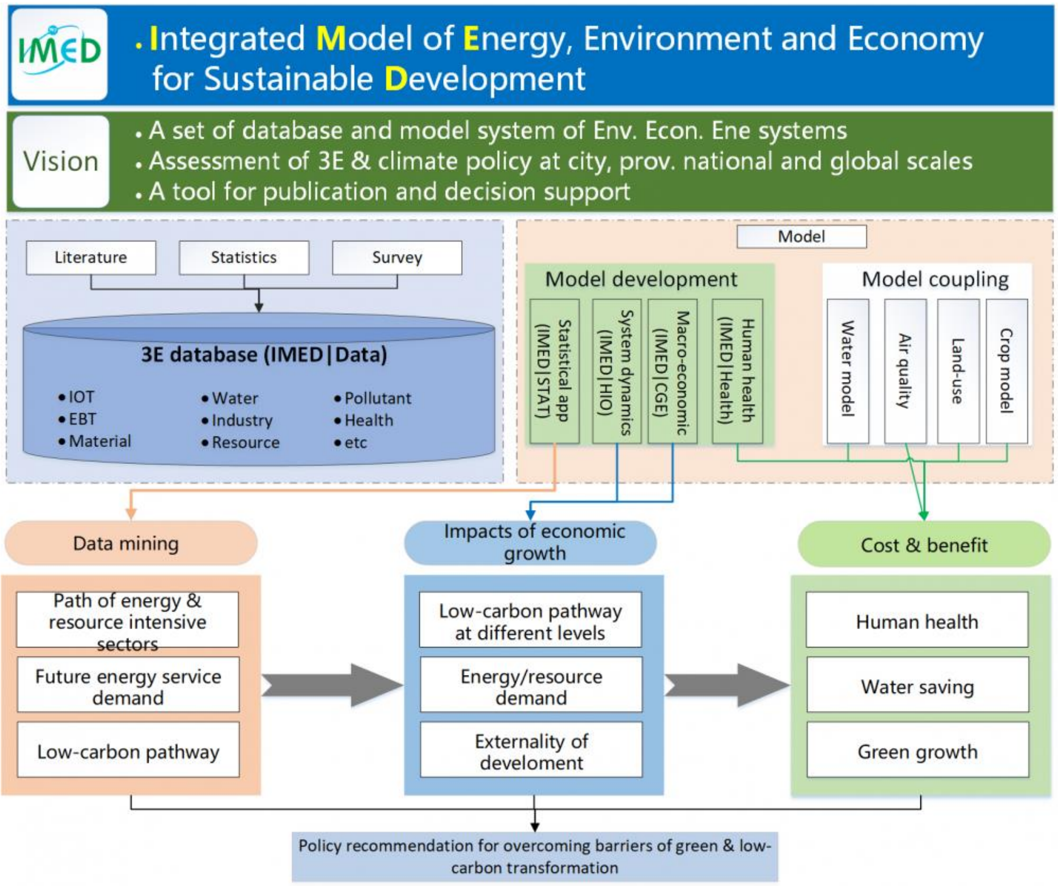

Figure 6. IMED model framework

3.5 GUIDE model

The GHGs and Air pollutants Unified Information DEsign System for Environment (GUIDE) is developed by Woo et al., Konkuk University. It aims to establish a decision-making system to manage GHGs and air pollutants simultaneously[8], with economy and energy projection, emission and air quality simulation, and cost-benefit decision making. For air quality simulation, it includes RSM model, as mentioned before, and divides Republic of Korea into 17 regions, with 7 air pollutants (CO, NOx, NH_3, SO_2, PM_{10}, $PM_{2.5}$, VOC) and six Kyoto greenhouse gases (CO_2, CH_4, N_2O, 3 F-gases) considered. The initial framework model is just developed in year 2020.

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[8] Slides by Woo Jung-Hun on Expert Consultation Meeting for NEASPEC Transboundary Air Pollution Project, Dec. 2016.

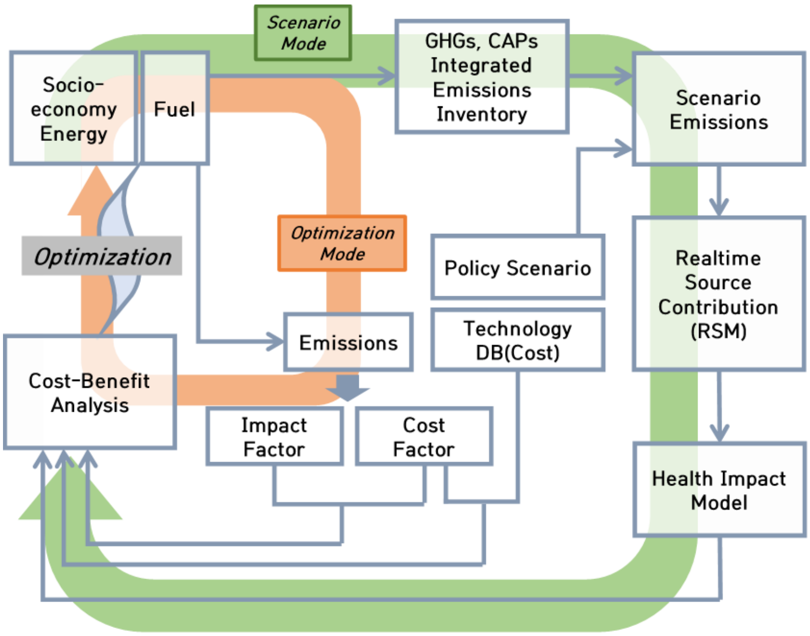

Figure 7. GUIDE framework (J.-H. Woo, 2020)

3.6 Other relevant studies in the sub-region

Other studies may not rely on integrated assessment models, but still there are integrated assessment measures used in those researches. Zhang et al. (2017a) showed that 30,900 (95% CI, 14,100–47,700) deaths in the 'rest of east Asia' region (which includes Japan and South Korea) were related to emissions in China. Compared to the result, 47,300 (95% CI, 20,300–74,400) deaths in eastern Europe were related to emissions in western Europe. GEOS-Chem and Global Burden of Disease Study (GBD 2013) were used. Other impacts such as visibility variation caused by aerosols are studied, with statistical model developed (Park et al., 2006).

Table 1. IAMs for air pollutants

Model name	Developer	Model Output	CTMs	Contribution	Insufficiency
RAINS/GAINS	IIASA	Pollutants concentration, optimized control strategy and control costs	EMEP, TM5	First IAM for air pollution control strategy analysis	Exogenous emission pathway, need to integrate other models or extra assumptions
ABaCAS	U.S. EPA, Tsinghua University	Pollutants concentrations, optimal control strategy, control benefits and costs	RSM	Real-time response in RSM model, integrated policy tools for cost-benefit analysis of control strategy	Exogenous emission pathway, lack of GHG species, developing linkage with GCAM-China to provide GHG emission and future scenarios
REACH	IEEE, Tsinghua Univ.	Emission pathways, pollutants concentrations, health and economic impact	WRF-Chem; WRF-CMAQ	Emission scenario with cost-benefit analysis, include economic impact of pollution	Only scenario analysis, lack of optimal control strategy analysis, higher computation costs due to the numerical CTM
IMED	LEEEP, Peking Univ.	Emission pathways, pollutants concentrations, health and economic impact	GAINS-China	Emission scenario with CGE model, integrate economy and health impact analysis	Only scenario analysis, lack of optimal control strategy analysis
GUIDE	Konkuk University	Emission pathways, pollutants concentrations, health and economic impact	RSM-Korea	Comprehensive GHGs and air pollutants synergy analysis	Initial development is finished in year 2020

IV. Discussion and Outlook

4.1 Conclusion of the review

This report briefly reviewed the studies on IAMs of air pollution in North-East Asia. We can see that processes of CRLTAP and outcomes from the IAMs are of high relevance to the work of NEACAP for identifying policy goals and effective control measures. The scientific community in North-East Asia has also utilized IAM for developing policy scenarios for mitigation options of air pollution mostly at national levels, but very limited at the level of North-East Asia sub-region. Fortunately, there are available IAMs which may be applied to this sub-region for comprehensive analyses of abatement cost and of air quality benefit. This work requires a multidisciplinary approach with the involvement of experts from diverse fields, up-to-date information on emission, energy system and technologies in key sectors, and government policies. Figure 8 proposes a framework for IAM methodology for assessing sub-regional and national air pollution in North-East Asia, which helps member countries to develop relevant air control strategy.

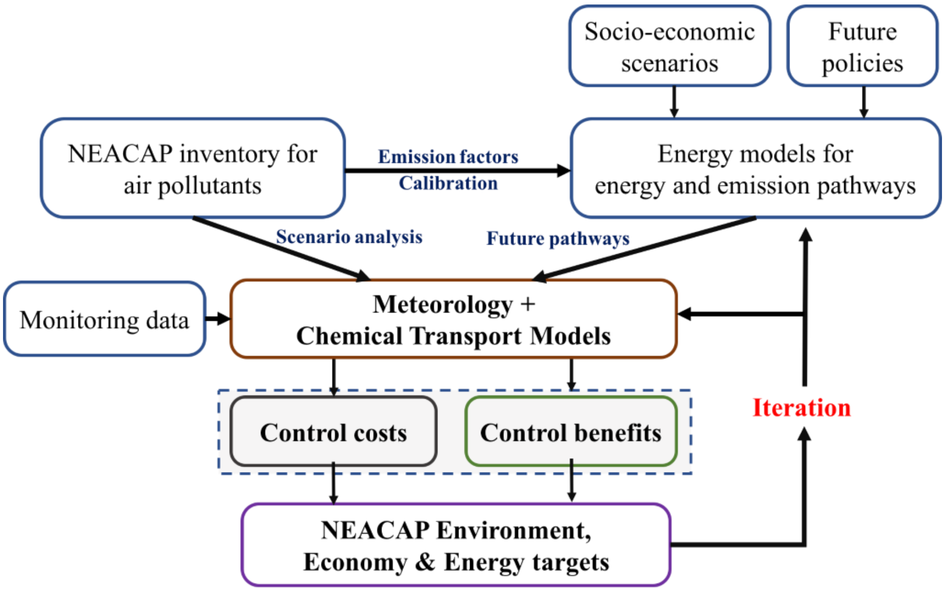

Figure 8. IAM framework for air pollutants in North-East Asia[9]

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[9] Note that the whole IAM framework may be implemented by one or more models. For example, GAINS model can cover most of those functions, with scenario analysis mode and optimization mode. Alternatives would be including other types of energy models or economic models for detailed customized emission pathways.

4.2 Proposed Approach and Modality for NEACAP's work on IAM

a. Aims and approach

IAMs can be used as a scientific and practical tool to help governments identify cost-effective emission reduction pathways and measures of air pollution and assist the mitigation of air pollutants both at nations and in the subregion.

Development of future emission scenarios in North-East Asia: In support of a joint strategy for air pollution reduction, future emission pathways will be developed based on inputs of future economic projection (GDP and demography), energy structure or pathway (as policy input or for IAMs calibration), end-of-pipe technologies penetration, and technology improvement (if possible, for example, the removal efficiency of end-of-pipe technologies, costs of electricity generation technologies, etc.). The future emissions shall be allocated into subsector (e.g. coal-fired power plant for instance) and technologies (i.e. USC for coal-fired power plant). For the comparability and credibility of model results, consensus on basic scenario pathways could be addressed under coordinate of Working Group on IAMs (WGIAM) (see below, similar to IPCC SRES, RCPs or SSPs common scenarios), such as North-East Asia socio-economic pathways, sub-regional trade and collaboration scenarios, status quo and potential policy tools, etc.

Development of an overall approach to IAMs and comparative analyses: With the progress of energy and climate researches, a range of IAMs are developed. Different IAMs are developed with different methods and have different conditions on policy application. The top-down models such as CGE models are widely used for development of future emission pathways, the economic impact and the social costs of control strategies. However, such models can only be allocated to subsector level, and are lack of technology representation. Bottom-up models such as optimization model (MESSAGE by IIASA, MARKAL/TIMES by IEA) and market equilibrium model (GCAM by PNNL) have the detailed representation of technologies. However, detailed technology parameters are needed especially for future scenario design. Air quality based IAMs such as GAINS (regional and national versions) and ABaCAS could be linked to scenario generating models and derive clean air solutions. Thus, model comparison would be conducted by synergizing with existing efforts (e.g. MICS-Asia, CAAC) for developing clean air solutions.

Development of science-based clean air solutions utilizing multiple IAMs and taking into account national social-economic circumstances and policies: Policy goals, priority areas and clean air solutions will be proposed based on the results of multiple IAMs and linked with national target and policies. An ensemble approach that builds on the outcomes of multiple IAMs will be taken to make the process inclusive for diverse groups and enhance credibility of the outcome as a reference for policy and technical cooperation. The cost-effectiveness of clean air measures and sub-regional air quality improvements will be evaluated with up-to-date information. These outcomes of IAMs can also provide technical and scientific support to the development of NEACAP Scientific Assessment

Report and other policy evaluation frameworks, which will enhance the information exchange on the impact and trend of air pollution at the sub-regional level.

b. Institutional arrangements

A WGIAM shall be established in 2020. The composition and operation of the WGIAM would take a flexible and practical approach without limiting the number of members from each country. The nomination of WGIAM members will base on the relevant expertise of the expert/institute. The nomination will be made by SPC members in accordance with required procedures in his or her government. The Working Group is responsible for collection of clean air information, development of future emission scenarios, evaluate the cost-efficient measures, and propose sub-region and/or national clean air policy recommendations. Members of the Working Group on IAMs may include but not limit to the expertise on emission inventory, energy planning, control technologies and costs, atmospheric modeling, health and ecological impacts.

To facilitate the IAM research collaborations and provide a platform enhancing the scientific exchange, capacity building and training among partners, a Technical Center on IAMs shall be established with approval of SPC. The responsibilities of the Technical Center are to develop the detail work plan of IAMs under NEACAP, to compile the information and data input from members of Working Group, to compare the IAM results of multiple models, to organize the annual workshops/trainings and review outcomes of IAMs, to participate the activities of other Working Groups/scientific networks, and to consult with national experts and other stakeholders. Considering the model limitations and uncertainties, an ensemble approach that build on model results from a combination of work from multiple models/multiple teams may be used under the request by Technical Center.

4.3 Proposed IAMs work

The main goals of the IAMs are to propose the future emission pathways for the sub-region of North-East Asia in a certain time period, studies on the effectiveness of control strategies, and impact of air pollution on human health and environment and propose the cost-effective control measures. Conducing IAMs will involve but not limited to the following activities:

a. Facilitating institutions to participate in IAMs on emission pathways and cost-effective control measures in North-East Asia

Since different IAMs run with different methodologies, social and economic systems structures, etc., NEACAP will take the “ensemble” approach, inter-comparison of results from different IAMs, and facilitate relevant institutions to participate in IAMs. For example, there are relevant institutes available for the joint model research: IIASA with GAINS-Asia (with energy scenarios from IEA World Energy Model); Division of Air Pollution and its Control at School of Environment, Tsinghua

University with GCAM-China (bottom up model for emission pathways) and ABaCAS (for air quality control and cost-benefit analysis); Institute of Energy, Environment, and Economy, Tsinghua University with REACH model (top-down CGE model for emission pathways); NIES with AIM (CGE for emission pathways); Division of Interdisciplinary Studies, Konkuk University with GUIDE model.

For the comparability and credibility of model results, consensus on basic scenario pathways could be addressed under coordination of TCIAM and WGIAM (see below, similar to IPCC SRES, RCPs or SSPs common scenarios), such as North-East Asia socio-economic pathways, sub-regional trade and collaboration scenarios, status quo and potential policy tools, etc.

b. Comparing the results of IAMs including through annual gathering of modeling results:

It is necessary to discuss and exchange modeling results between different model teams within a certain time interval, e.g. annually. Model teams will show model results and research conclusions at discussion meeting, and together with experts from NEACAP, and discuss inputs for emission pathways and control measures.

c. Developing a report as a reference for technical and policy cooperation

The expected results include: emission pathways; control scenario analysis with costs and benefits from IAM models; the optimized control target or pathway for North-East Asia. Those results and methodologies will be developed as a key reference for technical cooperation and policy dialogues under NEACAP.

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