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Industrial Sector Energy Efficiency Modeling (ISEEM) Framework Documentation

Author
Karali, Nihan

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Nihan Karali
Tengfang Xu
Jayant Sathaye

Environmental Energy Technologies Division

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Industrial Sector Energy Efficiency Modeling (ISEEM) Framework Documentation

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Prepared by

Nihan Karali
Tengfang Xu
Jayant Sathaye
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
Berkeley, CA

Prepared for
Eric Smith
Climate Economics Branch
Climate Change Division
U.S. Environmental Protection Agency

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General Acronyms

AGE	Applied General Equilibrium Models
CES	Constant Elasticity of Production
CETA	Clean Energy Technology Association Model
CGE	Computable General Equilibrium Model
CIMS	Canadian Integrated Modeling System
CO_2	Carbon Dioxide
CRF	Capital Recovery Factor
DICE	Dynamic Integrated Model of Climate and the Economy
EU	European Union

EFOM	Energy Flow Optimization Model
ENVEES	Energy-Economy-Environment Model
EPPA	MIT Emissions Prediction and Policy Analysis Model
ERIS	Energy Research and Investment Strategies Model
ERM	Environmental Resources Management Model
ETA	Energy Technology Assessment Model
GEM-E3	Global Energy Model
FUND	Climate Framework for Uncertainty, Negotiation and Distribution Model
GAMS	General Algebraic Modeling System
G-CUBED	A Multi-Sector Inter-temporal General Equilibrium Model
GCAM	Global Change Assessment Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GTAP-E	Global Trade Analysis Project - Energy
GREEN	A Global Model for Quantifying The Costs of Policies to Curb CO_2 Emissions
HERMES	Harmonized Econometric Research for Modeling Economic Systems
IA	Integrated Assessment
ICAM	Integrated Climate Assessment Model
IEA	International Energy Agency
IIAM	Indian Institute of Management Model
IMAGE 2.0	Energy-Industry System Model
ISEEM	Industry Sector Energy Efficiency Model
IO	Input Output
LEAN	Lean Management for the Energy Model
LEAP	Long-Range Energy Alternatives Planning System Model
LP	Linear Programming
MARKAL	Market allocation Model
MDM	Multi-sectoral Dynamic Model
MEPA	Massachusetts Environmental Policy Act Model
MERGE	Integrated Assessment Model for Global Climate Change
MESSAGE	Model For Energy Supply Systems And Their General Environment

MIDAS	Multinational Integrated Demand and Supply Model
MINICAM	Mini-Climate Assessment Model
MIS	Macroeconomic Information System Model
NEMS	National Energy Modeling System of USA
NLP	Non-Linear Programming
OECD	Organization for Economic Co-operation and Development
PJ	Peta Joule
POLES	Prospective Outlook on Long-Term Energy Systems Model
POLES	Global Energy Supply, Demand, Prices Forecasting Model
PRIMES	The Primes Energy System Model
RICE	Regional Integrated Model of Climate and the Economy
SCREEN	Hybrid Bottom-Up Computable General Equilibrium Model
SGM	Second Generation Model
SLICE	Stylized Integrated Assessment Model of Climate and the Economy
TIMES	The Integrated MARKAL-EFOM System
U.S.	The United States
US DOE	The United States Department of Energy
US EPA	The United States Environmental Protection Agency
WIAGEM	World Integrated Assessment General Equilibrium Model
WORLDSCAN	A Model for International Economic Policy Analysis

Model Acronyms

act	Activity level of a technology
af	Annual availability factor
anninvcost	Annualized investment cost of a technology
bound_x_fix	Fix bound on technology activity/capacity/investment
bound_x_lower	Low bound on technology activity/capacity/investment
bound_x_upper	Up bound on technology activity/capacity/investment
cap	Capacity level of a technology
content	Rate of impurity in the input framework
crf	Capital recovery factor
crfdisc	Annualization/discount parameter

cum	Cumulative capacity of a supply technology
df	Net discount factor
dm	Demand service
decayi(e)	Maximum decay of import/export between consecutive
decayr	Maximum decay of supply between consecutive periods
decayt	Maximum decay of capacity between consecutive periods
dcost	Total discounted cost of a region
demand	Demand for an energy service
denvcost	Total of discounted environmental costs
dinvcost	Total of discounted investment costs
discinvcost	Discounted investment cost of a technology
domcost	Total of discounted operational costs
dsupplycost	Total of discounted supply costs
dtradecost	Total of discounted trading costs
discount	Discount rate
e	Energy source/raw material
emis	Emission level due to production activity
emisact	Emission emitted per unit of activity
emistrade	Level of emission emitted per unit of trading activity
emis_t	Emission level due to trading activity
export	Export level
exportcost	Unit cost of export to static region
envcost	Cost of per unit process based emission
envtrade	Cost of per unit trading based emission
fixom	Fixed operation and maintenance cost
growthr	Maximum growth of supply between consecutive periods
growtht	Maximum growth of capacity between consecutive periods
growthx	Maximum growth of import/export between consecutive
import	Import level
importcost	Unit cost of import from static region
inpent	Level of input requirement per unit of activity
inv	Investment level on a technology
invcost	Investment cost per unit of new capacity
life	Life time

m	Set of technologies
nyrp	Number of years per period
outent	Level of output generation per unit of activity
p	Process technology
p_i	Intermediate technology
p_e	Onsite electricity generation technology
p_d	Demand technology
prodcost	Total production cost of imported products
r	Trading region
resid	Level of residual capacity
s	Supply technology
subsidy	Rate of subsidy applied on any supply price
supcost	Unit supply cost
s_i	Import technology
s_d	Domestic technology
t	Period
tariffx	Tariff rates applied on import/export of a region
transportcost	Cost to transfer per tonne of a product per unit distance
totalcost	Net present value of the total cost for all periods
totalemis	Total emissions of a region at a period
ucost	Total undiscounted cost of a region
uenvcost	Total of undiscounted environmental costs
uenvcost_p	Total of process based undiscounted environmental costs
uenvcost_t	Total of trading based undiscounted environmental costs
uinvcost	Total of undiscounted investment costs
uomcost	Total of undiscounted operational costs
usupplycost	Total of undiscounted supply costs
utradecost	Total of undiscounted trading costs
unit	Unit conversion factor
v	Emission type
varom	Variable operation and maintenance cost
w	Any region of the model

ISEEM Modeling Framework Documentation

1. Introduction

Interest on greenhouse gas (GHG) emission reductions in industry sectors in recent years has increased with the need to mitigate climate change in global, regional, and national scales (e.g., international obligations towards reducing carbon emissions and new climate-change legislations concerning industrial sectors in various countries). Particular attentions are given to environmental concerns and GHG emission reduction alternatives especially in the energy intensive manufacturing sectors such as iron and steel and cement sectors. The International Energy Agency (IEA, 2007) forecasts that industry accounts for nearly one-third of the total global primary energy use at more than 147 EJ (3,510 Mtoe) in 2004. Some reduction alternatives include direct financial investments on energy efficiency, renewable energy, and emission reduction technologies to reduce one's own fossil-fuel energy consumption. In recent years, studies at Lawrence Berkeley National Laboratory (Sathaye et al. 2010; Xu et al. 2010&2012) have focused on developing bottom-up representation of energy efficiency measures and cost curves of the mitigation technologies in key industrial sectors including iron and steel and cement in the United States (U.S.) and other countries. The studies have found that significant potentials exist in cost effective energy savings and carbon-emission reduction in both sectors, and that the estimated costs of saved energy and carbon reduction varied significantly across measures, sectors, and countries. For example, in the U.S. cement making sector, cost effective measures contributed to final energy savings in the range of 17-27% of the sector’s annual energy use, and carbon-emission reduction equal to 9-13% of the sector’s annual carbon emissions in the past. In the steel sector, cost effective efficiency options contributed to final energy savings in the range of 14%-26% of the total energy use annually, and carbon-emission reduction from 12% to 25% of total carbon emissions.

In order to achieve carbon-emission reduction goals, international commodity trading with other countries can be an alternative to reducing regional or national carbon emissions. For example, the share of imports of total product availability in the U.S. can be increased (e.g., from large emerging economies such as China and India), while the share of domestic production is being decreased. However, simply decreasing carbon emissions from the U.S. industries alone by increasing commodity imports might not necessarily result in reducing net global carbon emissions or global risks in climate change. Commodity trading strategy might also result in simply transferring actual production burdens to another country where actual intensities of energy use and emissions could be higher. Therefore, a market tool such as carbon trading via carbon offset between countries (e.g., between the U.S. and China or India) can be considered as another alternative to complying with caps on the total amount of carbon emissions allowed to emit. Offsets are typically achieved through financial support of renewable and energy efficiency projects that reduce GHG emissions. Good quality offsets that provide desirable environmental benefits can be cheaper or more convenient alternatives to reducing one's own energy consumption. Energy efficiency technologies can provide viable alternatives to carbon reduction associated with energy use in industrial sectors.

Because international trading partners such as the U.S., China, and India have unique characteristics in industrial sectors and raw material supplies and constraints, it is necessary to investigate "least cost" alternatives for lowering net global carbon emissions. Improving energy efficiency, development and implementation of new energy technologies and resources, and advancing understanding of their impacts on energy system cost structure are crucial to achieve the goals of global carbon-emission reduction.

In recent years, various global and national energy, environment, and climate models have been developed for studies on energy strategy and planning. These models have different features and are often based on different methodological approaches. However, although they are useful in predicting future trends (e.g., future energy consumptions and emissions), many of them consider the system as a whole and disregard the relationships between nations. Often, these are global or regional framework used to model energy systems and sectors of the selected nations that are independent of each other (i.e., they ignore trading relationships and possible variations in production and energy consumption due to changes in trading volumes). There has not been a tool that is specifically developed to evaluate and predict future commodity and carbon trading as an alternative for carbon-emission reduction.

The goal of this study is to develop a new bottom-up industry sector energy-modeling framework with an agenda of addressing least cost regional and global carbon reduction strategies, improving the capabilities and limitations of the existing models that allows trading across regions and countries as an alternative. The regional structure of the framework is designed to allow modeling of commodity trading on the national level. In addition, the open structure of the framework also provides the user suitable environment to implement refinements and modifications that might be needed for a particular analysis. Using the new model is expected to develop new information and knowledge that can assist decision-making in advancing comprehensive energy strategies and carbon reduction planning for the industrial sectors.

The remainder of this report is organized as follows. Section 2 presents a brief literature review on existing energy climate models, typical approaches to top-down, bottom-up, and hybrid modeling, and a major classification tabulated by disaggregation and region. Section 3 provides the objectives that have inspired development of the new framework in this study. Section 4 defines the new modeling structure and methodology used. Section 5 describes the new modeling framework along with variable types and definitions; objective function contents; constraint types, classes, definitions, parameters, and representations. Section 6 provides a brief summary of the industry sector energy efficiency modeling (ISEEM) framework and its potential applications.

2. Literature Review of Relevant Energy Modeling

The development and varieties of energy modeling methodologies over the past four decades have generated diverse modeling literature (Fisher-Vanden *et al*., 1993; Lazarus *et al*., 1997; Loulou *et al*., 2004a; Loulou *et al*., 2004b; Nordhaus, 1994; Schrattenholzer, 1981). Figure 1 illustrates typical energy modeling systems. The energy modeling systems typically seeks for cost minimization or utility maximization as the objective, while satisfying energy demands based on supply, technology, economy, and environmental characteristics and limitations (Karali, 2012). The components in the diagram may differ depending on how energy demands are defined in the modeling system. For example, common energy modeling systems define energy demands exogenously, which are generated in separate economic models. In other modeling systems, the demand input is defined by combining with economy modeling components. The horizontal dotted line in Figure 1 indicates the relationship and separation between energy sector modeling and economic modeling.

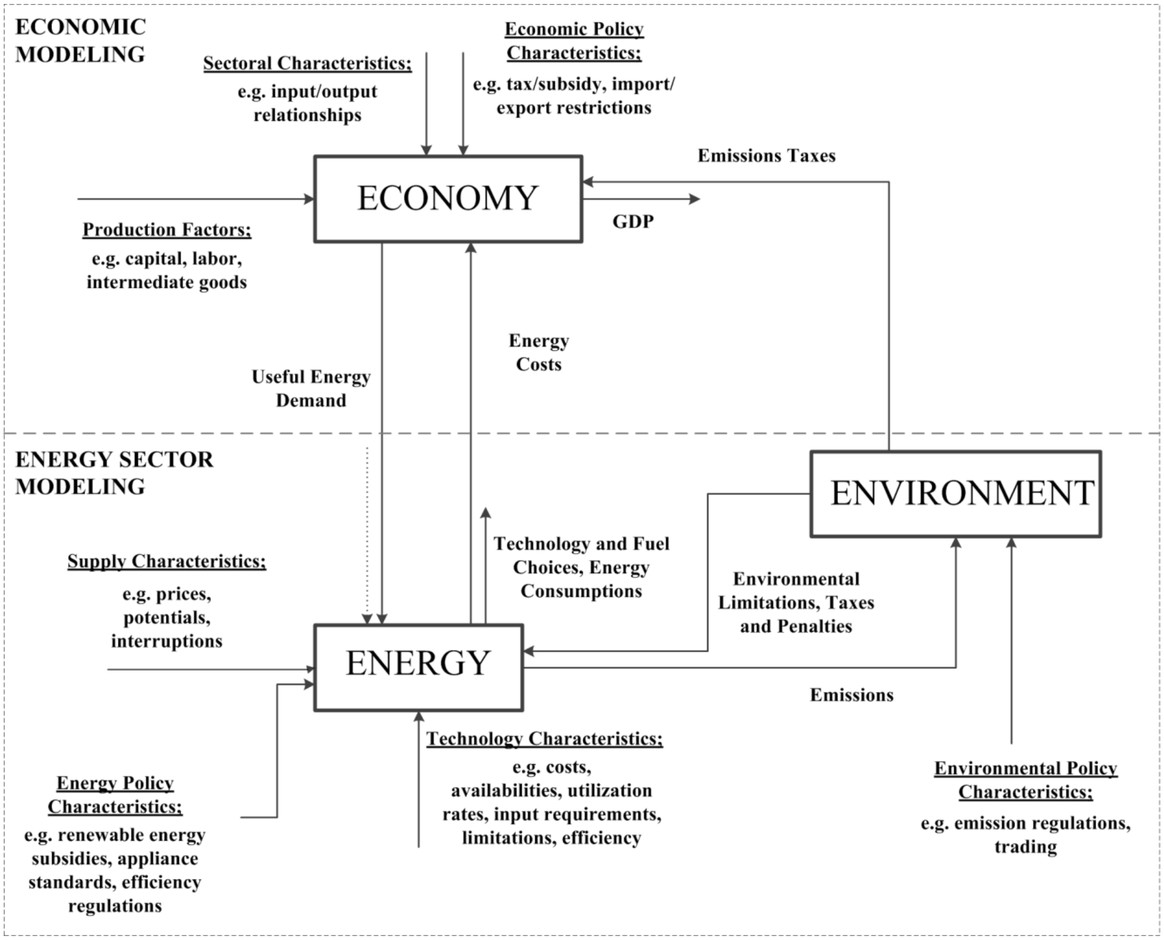

Figure 1. Typical components of energy modeling systems

Many frameworks differ from each other depending on their disaggregation levels, energy sector representations, geographical scopes, and time horizons. However, classification by disaggregation levels is common (Hourcade *et al*., 2006). The technologically disaggregated models, namely *bottom-up models*, are partial equilibrium representations of the systems. They provide a detailed technological representation and typically include no or very limited interactions with the macroeconomic system (Karali, 2012). On the other hand, the aggregated models, namely *top-down models*, have a macroeconomic perspective and mainly focus on the relations of the energy sector with other sectors of the economy (Karali, 2012). The sectoral economic activities are represented through aggregate production functions. However, their energy-economy interactions have a limited representation in the energy system.

Karali (2012) reviewed and classified energy models in several different categories. Table 1 highlights the findings from a portion of relevant models (Karali 2012). There are three typical modeling approaches: 1) top-down models, 2) bottom-up models, and 3) hybrid models. *Top down models* adopt an economy-wide perspective. They can support analysts in assessing the macroeconomic impacts (e.g., gross domestic product (GDP), consumption, investments, and foreign exchange) of particular market instruments (e.g., carbon tax on energy system or subsidies on renewable energy generation). However, they are mostly criticized for not capturing the necessary detail from the energy sector and underrepresenting the complex interactions among demand and supply options (IPCC, 2001). Top-down modeling typically excludes technological details of energy production or conversion, and is unable to incorporate different assumptions about how discrete energy technologies and costs will evolve in the future. *Bottom-up models*, on the other hand, represent the energy system with a technology rich description and put the emphasis on the correct description of energy sources and technologies. However, such models often neglect the macroeconomic impacts of energy policies. *Hybrid models*- are the frameworks aiming at uniting both top-down and bottom-up approaches, by simply combining technological explicitness of bottom-up models with the economic comprehensiveness of top-down models (Hourcade *et al*., 2006). However, in hybrid modeling both bottom-up and top-down portions are simplified for the computational purposes (i.e., to make the model computable); therefore, hybrid models typically has limitations in the amount and details of input and output compared to a top-down or bottom-up model.

Each model type can be further classified by disaggregation level and geographical representation. For example, the top-down disaggregation is sub-divided into input-output (IO), integrated assessment (IA), computable/applied general equilibrium (CGE/AGE), and econometric models. For each disaggregation level, the model can be developed for different geographical representation (e.g., national and/or global). Bottom-up models are categorized as linear programming (LP) or nonlinear programming (NLP) models, which are often developed to address national representation.

Table 1. Classification of Common Energy Models

		National	Global	Global-regionalized
Top-Down Models	**IO Models**	MIS MEPA		
	IA Models		DICE RICE SLICE CETA GCAM	IMAGE 2.0 (13 world regions) RICE (6 world regions) FUND (9 world regions) MERGE 3 (5 world regions) ERIS (9 world regions)) IIAM (26 world regions) ICAM (7 world regions) GCAM (14 world regions)
	CGE/AGE Models	Conrad (D) Bovemberg-Goulder (U.S.) Jorgenson-Wilcoxen (U.S.) GEM-E3 LEAN HERMES	GTAP-E	ERM (9 world regions) EPPA (12 world regions) SGM (20 world regions) GREEN (12 world regions) G-CUBED (8 world regions) Whalley-Wigle (6 world regions) WIAGEM (25 world regions)
	Econometric Models	MDM		WORLDSCAN POLES
Bottom-Up Models	**LP/NLP Models**	MARKAL TIMES MESSAGE EFOM LEAP MIDAS PRIMES		TIMES IEA-MARKAL (10 world regions)
Hybrid Models		MARKAL-MACRO NEMS ENVEES ETA-MACRO HERMES-MIDAS SCREEN MESSAGE-MACRO		CIMS

Note: Citations for the models listed in the table: (Peck and Teisberg, 1992): CETA, (Murphy et al., 1997): CIMS, (Nordhaus, 1994): DICE, (Van der Voort, 1984; Van der Voort et al., 1985): EFOM, (Arikan and Kumbaroglu, *2001): ENVEES, (Yang et al., 1996): EPPA, (Bareto and Kypreos, 2000; Capros and Chryssochoides, 2000): ERIS, (Barns D. et al., 1992): ERM, (Manne, 1977): ETA-MACRO, (Tol, 1997): FUND, (Smith et al., 2010): GCAM, (Gjerde et al., 1998): G-CUBED, (Burniaux and Truong, 2002): GTAP-E, (Mot et al., 1989): HERMES, (Capros and Karadeloglu, 1992): HERMES/MIDAS, , (Dowlatabadi, 1998): ICAM, (Bernstein et al., 1997): IIAM, (Alcamo, 1994): IMAGE 2.0, (Lazarus et al., 1997): LEAP, (Barker, 1994; Nordhaus and Yang, 1996): RICE, (Loulou et al., 2004a): MARKAL, (Loulou et al., 2004b): MARKAL-MACRO, (Manne A. and Richels, 1992): MERGE, (Messner and Strubegger, 1995: MESSAGE, (Gritsevskyi and Schrattenholzer, 2003): MESSAGE-MACRO, (Barker, 1994): MDM, (DOE 2009): NEMS, (Loulou et al., 2005): TIMES, (Kumbaroğlu and Madlener, 2003): SCREEN, (Fisher-Vanden et al., 1993): SGM, (Kolstad, 1994): SLICE, (Kemfert, 2002): WIAGEM.*

Definitions for modeling terminology:

Macro Economic Models: Macro economic models focus on the entire economy of a society and on the interaction between the sectors (on the short or medium term).

General Equilibrium: General equilibrium models are used to study the energy sector as part of the overall economy and focus on interactions between the energy sector and the rest of the economy (on the medium to long term). General equilibrium is determined on all markets simultaneously.

Partial equilibrium: Partial equilibrium analysis focuses on a small part of the economy, often on a two-commodity world. In contrast to general equilibrium models, partial equilibrium models imply that only a single market is considered at a time).

The following further discussed some examples for the above mentioned modeling approaches, their applications and limitations.

Top-down Models: Applications and Limitations

Input-output analysis was developed by Wassily Leontief in the late 30's (Leontief, 1936). These models are based on a system of linear equations that represent an economy as a number of industries (Karali, 2012). Input-output analysis shows the process, by which inputs in one industry sector produce outputs for consumption or for input into another industry sector. Examples of this modeling approach include the MIS (Macroeconomic Information System) model of Kemfert and Kuckshinrichs, 1997 and the MEPA (Massachusetts Economic Policy Analysis) model of Stevens et al., 1981. The IO models are considered as simple linear models, representing rough approximations of the inputs required. However, they are mostly criticized for missing the feedback mechanism between energy demands and supplies (Rosenbluth, 1968). Since there is no feedback mechanism, the impact of an exogenous stimulus (such as energy prices or supply limitations) on a sector can only be seen on the input-output path. However, in a real system, all sectors are related and there are many cross impacts.

An integrated assessment (IA) model is defined as a combination of scientific and socio-economic aspects of climate change (Bernstein *et al.*, 1997; Capros and Chryssochoides, 2000; Dowlatabadi, 1993; Edmonds and Reilly, 1983; Manne *et al.*, 1995; Rotmans, 1990; Tol, 1997).

The purpose of this modeling approach is to assess the impacts of climate change control policies over a wide knowledge from multiple disciplines (Tol, 2002; Weyant *et al*., 1996). Examples of IA models include the DICE (Dynamic Integrated Climate Change) model of Nordhaus (1994), the MERGE (An Integrated Assessment Model for Global Climate Change) model of Manne *et al*. (1995), the CETA (A Model for Carbon Emissions Trajectory Assessment) model of Peck and Teisberg (1992), GCAM (Global Change Assessment Model) model of Smith *et al*. (2010), and the IMAGE 2.0 (Integrated Model to Assess the Greenhouse Effect) model of Alcamo (1994). IA models are mostly criticized for offering contrasting results that depends on critical assumptions and underestimations about transmission channels between policies and relevant variables such as economic growth rates for energy intensive industries (Cantore, 2009). Most IA models tie GHG emissions to industrial production either implicitly through emissions projections or explicitly through an actual model of industrial production (Tol, 2002). However, economic growth is, at the same time, directly affected from advances in technology and population growth. IA models miss those links between economic growth and population growth and advances in technology.

On the other hand, from the beginning of the 1990's, CGE modeling has become a widely used tool for analysis of energy and environmental policy issues (Barns *et al*., 1992; Bovenberg and Goulder, 1996; Capros *et al*., 1995; Conrad, 1999; Fisher-Vanden *et al*., 1993; Gjerde *et al*., 1998; Jorgenson *et al*., 1992; Kemfert, 2002; Whalley and Wigle, 1992; Yang *et al*., 1996). The energy sector, like non-energy sectors, is mostly represented in an aggregate way by means of production functions, which capture substitution possibilities through elasticity of substitution (Karali, 2012). Mostly, these production functions distinguish between the input factors (such as?) capital, energy and labor, and their substitution elasticity has to be given exogenously (Kemfert, 1998). Therefore, each sector is represented by a production function, which is designed to simulate the potential substitutions between the main factors of production. A most typical one is the Constant Elasticity of Production (CES) function, which is a type of production function that displays constant elasticity of substitution. There have been many efforts to study energy-economy-environment interactions using CGE models. Examples in this regard are the OECD (Organization of Economic Co-operation and Development) model GREEN (A Global Model for Quantifying The Costs of Policies to Curb CO_2 Emissions) of Burniaux *et al*. (1992), the EU (European Union) model GEM-E3 (Computable General Equilibrium model for Studying Economy-Energy-Environment Interactions) of Capros *et al*. (1995), the SGM (Second Generation Model) model of Fisher-Vanden *et al*. (1993), HERMES (Harmonized Econometric Research for Modeling Economic Systems) model of Mot *et al*. (1989), and GTAP-E (Global Trade Analysis Project - Energy) Model of Burniaux and Truong (2002).

Bottom-up Models: Applications and Limitations

Compared to top-down models, bottom-up models represent the energy system with a technology rich description and put the emphasis on the correct description of energy sources and technologies (Capros, 1993; Capros and Karadeloglu, 1992; Fishbone L.G. *et al*., 1983; Loulou *et al*., 2004a; Schrattenholzer, 1981; Van der Voort *et al*., 1985). Bottom-up energy system models are partial equilibrium representations of the energy sector. They provide a great number of discrete energy technologies to capture substitution of energy sources on the primary and final energy level, process substitution, or efficiency improvements. Each energy consuming technology is identified by a detailed description of input-output structures, cost dynamics, and other technical and economic characteristics. However, such models often neglect the macroeconomic impacts of energy policies. Bottom-up energy system models are typically cost as optimization problems, which compute the least-cost combination of energy system activities to meet a given demand for final energy or energy services subject to technical restrictions and energy policy constraints (Karali, 2012). There is a variety of partial equilibrium models such as the EFOM (Energy Flow Optimization Model) model of Van der Voort *et al*. (1984), the MARKAL (Market Allocation Model) model of Fishbone and Abilock (1981), the MESSAGE (Model for Energy Supply Systems and Their General Environment) model of Schrattenholzer (1981), the MIDAS (Multinational Integrated Demand and Supply Model) model of Capros and Karadeloglu (1992), and the PRIMES model of Capros (1993).

Hybrid Models: Applications and Limitations

The limitations of top-down and bottom-up approaches have resulted development of integrated frameworks. These groups of models combine technological explicitness of bottom-up models with the economic comprehensiveness of top-down models. However, those models lack the details developed in the two modeling approaches. Examples in this field are the NEMS (National Energy Modeling System) model of the US DOE (The U.S. Department of Energy) (2009), the MARKAL-MACRO (MARKAL combined with a Macro Model) model of Manne and Wene (1992), the HERMES-MIDAS (combination of HERMES and MIDAS models) model of Capros and Karadeloglu (1992), the MESSAGE-MACRO (MESSAGE combined with a Macro Model) model of Gritsevskyi and Schrattenholzer (2003), and the ETA-MACRO (Energy Technology Assessment Model (ETA) combined with a Macro model) model of Manne (1977).

Although the energy modeling frameworks discussed here are capable of projecting future trends, they disregard the possible trading relationships and variations in production and energy consumption due to changes in trading volumes between the nations. Therefore, these global or regional modeling frameworks can only model the energy systems and sectors of a nation independent of those of other nations or regions in the model.

In order to better understand emission reduction impacts of commodity and carbon trading that take into account of end use energy technologies adopted in different countries, there is a need for developing a new modeling approach that considers cost optimization of emission reduction while allowing commodity and carbon trading. Top-down or hybrid modeling approaches would not be suitable for those kinds of analysis since it is not possible to include technological (engineering) details that would enhance energy efficiency or emission reduction potentials of an investment decision in any top-down or hybrid modeling approaches. Hourcade et al. (1996) state that technological change in most of the top down models is represented by the autonomous energy efficiency index and the elasticity of substitution between the aggregate inputs such as capital, labor, and energy. Those representations make it difficult to convert detailed technological projections into the production functions of top –down models. The technological representations in the hybrid models are also kept limited for the computational easiness and simplicity.

In contrast, bottom-up approaches use highly disaggregated data to describe energy end-uses and technological options in detail. Therefore, a bottom-up modeling would be the most suitable approach for that type of analysis. However, t none of the existing bottom-up models consider commodity or carbon trading relations (and their impacts on production, energy consumptions, and emissions) between nations.

3. Project Objective

The goal of this project is to develop a new bottom-up industry sector energy-modeling framework to address least cost regional and global carbon reduction strategies, with the capabilities of allowing trading across regions and countries as an alternative solution to carbon reduction. Using the new model, we expect to develop new information and knowledge that can assist decision-making in advancing comprehensive energy strategies and carbon reduction planning for the industrial sectors.

The technical objective of the project is to develop a bottom-up modeling that provides a suitable platform to include energy efficiency measures as mitigation options, as well as commodity and carbon trading as viable alternatives to carbon-emission reduction strategies. Specifically, the Industry Sector Energy Efficiency Model (ISEEM) framework is developed as a simple, flexible, linear optimization modeling framework that allows commodity and carbon trading between nations. The ISEEM framework can provide users with the ability to support specific energy studies or more general energy and carbon reduction policies.

The ISEEM modeling framework is focused on the mechanisms and relationships that would emulate any industry sector as realistically as possible, with the details that would enable analyzing the changes in energy consumption and carbon emissions. The complex relationships of supplying and producing energy sources and raw materials are represented with technological details. The ISEEM framework also allows to analyze the effects of various trading characteristics such as tariffs, import/export taxes, emissions due to commodity trading (i.e., international shipping), which are not available for analysis using the other modeling frameworks discussed in Section 2.

In addition, the structure design for ISEEM framework offers the flexibility and ease in adding new relations to the modeling system. Compared to models with well-defined rigid structures or interfaces that commonly prevent the user from adding new relations to the system, ISEEM framework provides a viable and favorable environment to build new relations based on what the user wishes to analyze .

4. Modeling Structure and Methodology

The ISEEM's main modeling system is a unified structure of sub modules and this modular structure allows the user to work either on narrow-scope projects (e.g., focusing on the energy consumption of a specific sector such as iron and steel sector) or wide-scope projects (e.g., focusing on the energy consumption of the whole industry sector).

The modeling structures and relations are built over linear equations using optimization programming. The linear programming makes the generated models computable and easy to track for possible errors.

The framework applies bottom-up approaches for the detailed description of technologies and energy end-uses in any industrial sector.

The ISEEM framework is a bottom-up linear programming optimization model that minimizes the total system cost over a set of constraints. The framework is developed using GAMS (General Algebraic Modeling System) optimization modeling interface. GAMS is a user-friendly, high-speed, and high-level modeling platform which enables the user to build large-scale models. For the optimization modeling, a set of constraints are specified and used to seek for the least cost scenarios. Those constraints are of several kinds and express the relationships that must be satisfied for proper representation of the associated industrial systems. The main groups of constraints include the balance constraints, which guarantee that total usage of any material remains less than or equal to its total supply, the periodic capacity constraints, which computes the available capacity of a production technology at a period, the activity-capacity constraints, which determine the level of available capacity of a production technology that is used in the period, the demand constraints, which ensure that demands are satisfied each period, the trade constraints, which match up the trading volumes between two nations/ regions, and the emission constraints, which may be used to set national or global emission limitations.

Parameters are the data input to an ISEEM model. They indicate the input requirements and output generations to/from each technology, describe the operations and limitations (e.g., availability factors, cumulative or periodic raw material and energy source supply bounds, production bounds, and trading bounds) of the individual technologies, and represent the demands for industry products. The demand projections are placed into the model for the entire planning horizon. They based on exogenous projections developed outside of the ISEEM model. Costs parameters, on the other hand, define the objective function of the system and are essential for the minimum cost solution. Raw material and energy source supply costs, subsidies, technology investment costs, process operation costs, tariffs and transport costs of trading materials, environmental taxes and costs can be listed as the main items of the ISEEM total cost objective function. Time period is another parameter defined by the user (e.g., one-, five-, or 10-year interval). A detailed description of all parameters and constraints is provided in Section 5.

Figure 2 shows the basic ISEEM modeling framework structure, including input data, main outputs (including commodity production, energy consumption, carbon emissions), and major relationships. With the goal to achieve least cost mix of technologies in this framework, the

ISEEM model structure is composed of four modules: Supply Module, Process Module, Trading Module, and Environmental Module.

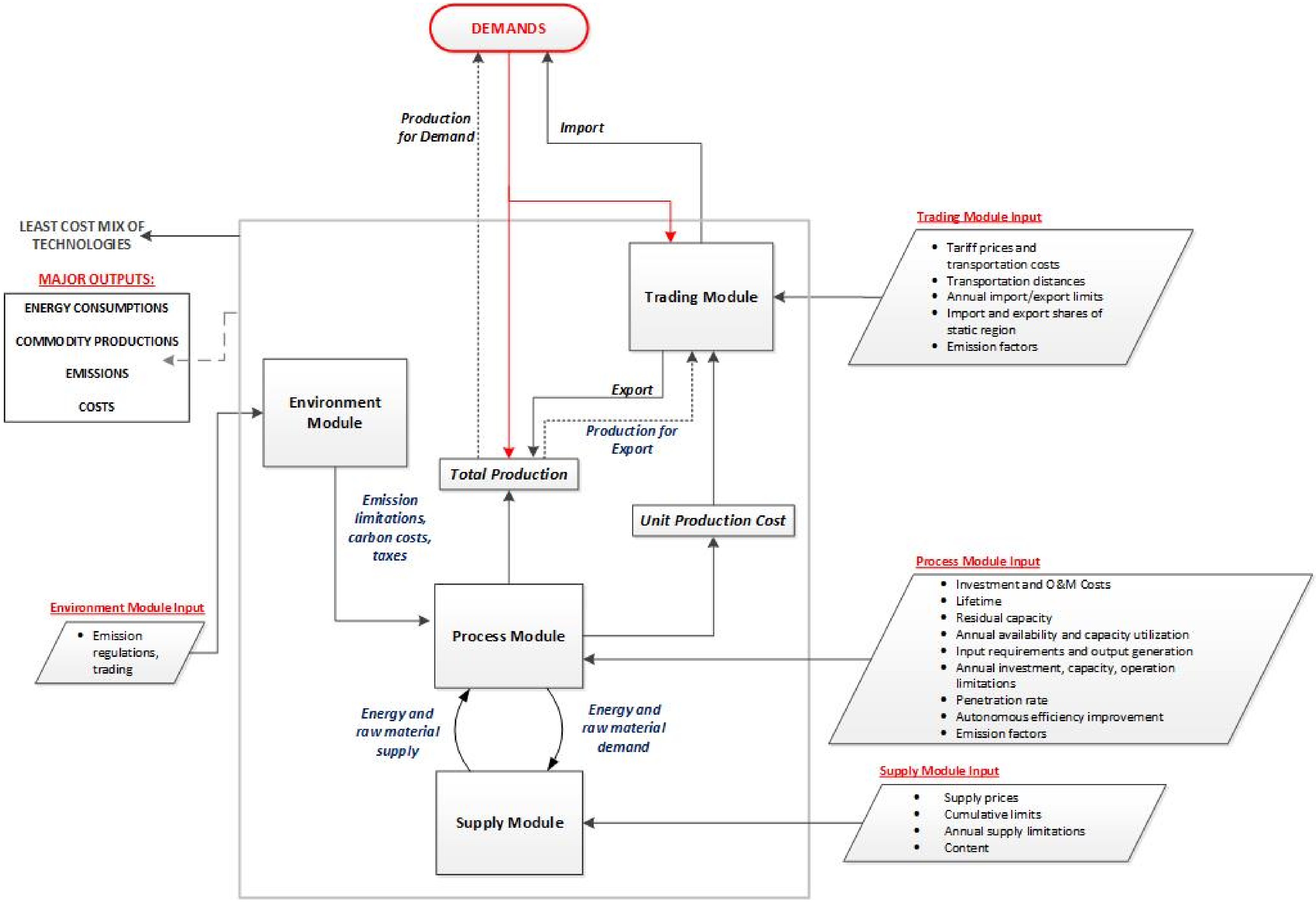

Figure 2. Basic ISEEM Framework Structure

Technology: Any mechanism processing, producing, supplying, or converting a product (i.e. energy sources, raw materials, intermediate products, final product) is referred to as a technology in the framework. Therefore, production processes and energy source/ raw material supply options are all represented as technologies. In other words, supply and process modules are structured over technology definitions and characteristics. Each technology has a unique parameter structure that determines its impacts on to the system (such as raw material consumption, energy source requirements, and environmental impacts, etc.). Costs, availability factors, limitations, input requirements, and unit output generation per technological activity can be listed as the main parameters related with the technologies. On the other hand, those technologies are linked to each other via product flows (i.e. input-output relationships). From this point of view, any output product produced by a technology is an input product to another technology. Technology characteristics (parameter and constraint structures) are formed based on the module the technology belongs to. Each technology in a module is associated with the same parameters and should satisfy the same constraints.

Supply module: Supply module includes the supply technologies that are responsible to supply raw materials and energy sources to the system. Those technologies can be defined for any type of supplies (like aggregated supply, domestic production, or import of any input source) with a unit cost and limitations on supply levels. Supply technologies do not need any input source to operate. In other words, they are the starting point of the process.

Process module: Process module defines the production system of the sector in each region. It includes the process technologies that generate a product by using another product as an input. Thus, the technologies in this module produce the intermediate and the final products of the system. Sector production facilities and onsite electricity generation facilities in the sector can be given as examples of technologies that can be defined under this module. The technologies that are responsible for producing the final product process the intermediate products to produce the final product (that will satisfy the demand requirements).

Trading module: The final product produced by process technologies is used to satisfy either demand of the region, in which the final product is produced, or demands of the other regions via trading relationships. Demands of the regions are determined outside of the model and exogenously placed to the system. Export and import levels, on the other hand, are endogenously determined in the trading module of the system. In other words, trading module allows import and export of the final product between regions. According to optimization process, if it is cost effective for a region to satisfy its demand via imports from another region or regions, the production in the region may be cut down or declined and import share might be increased. However, in this case, production and export levels of the other regions increase simultaneously (see Figure 3). Therefore, import and export levels between the regions are balanced in each period. In addition to active regions (i.e., the regions defined in an ISEEM model), a static region definition is established to calibrate an active region's trading with rest of the world (see Figure 4). The export and import of each active region to/from the static region are exogenously defined by the user for each period. Each region has to satisfy those trading volumes to/from the static region as well.

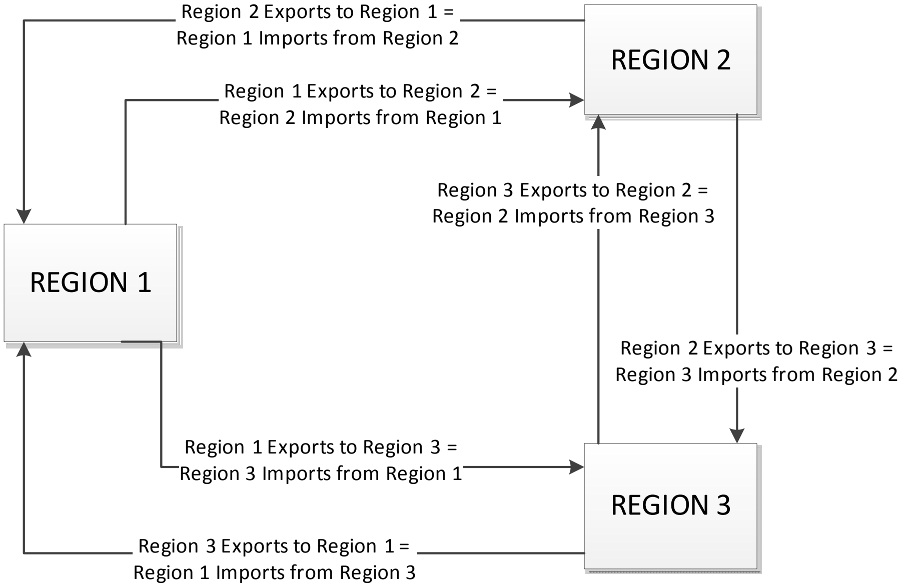

Figure 3. Trading Relationships Regarding Three Regions

Figure 4. Trading Relationships Regarding Static Region

The characteristics and relationships of technologies and modules are discussed in the following subsections in detail.

4.1. Supply Module

This module is formed by the supply technologies that are responsible for supplying energy sources and raw materials to the system. It is not possible to build a model, if there is no energy source and/or raw material supply in the system. There may be either a single source or multiple sources that supply the same product. For example, there may be different types of mines that produce the same raw materials (e.g. coking coal, iron ore, etc.) with different prices. The framework also allows division of energy source and raw material supplies into imported and domestic supplies. Imported supplies or sources are brought to the system by import technologies, while domestic sources typically represent mining technologies. Both supply technologies have similar characteristics with the division allowing users to create separate sets of supply technologies to be established for scenario analysis (e.g., for scenarios with which import amounts of iron ores or scraps in steel sector vary).

Table 2. Supply Technologies

Supply Technologies
Import Technologies
Domestic Technologies

Supply technologies only have activity variables (i.e., operation levels, to be determined by the ISEEM framework) as decision variables. These variables represent the levels of supplies from supply technologies when they operate. Typical units used are Peta-Joules (PJ, 10^{15}Joules) per year for energy sources and tonne per year for raw materials. Each supply technology is related with a unit supply cost, periodic decay or growth rates, and annual and cumulative bounds on supply levels. Annual bounds can be used for setting annual availabilities on energy sources or raw materials (a good example might be applying contract limitations for import sources). Cumulative bounds can limit the total supply of a supply technology over the planning horizon (a good example might be applying reserve capacity of mining resources). Decay and growth rates, on the other hand, can be used to limit the decay and growth of supply between consecutive periods. The annual and cumulative bounds on supply technologies are mostly used for calibration purposes. In summary, the key input parameters of supply technologies in an ISEEM model are:

- $bound\_x\_lower/bound\_x\_fix/bound\_x\_upper$: annual activity (supply) limits: lower bound, fixed bound, and upper bound,
- cum: cumulative limitation on total supply (overall resource supply),
- $decayr/growthr$: maximum decay (or growth) rate of activity (supply) between the consecutive periods,
- $subsidy$: price reductions that may be applied on raw material or energy costs,
- $supcost$: unit supply cost, i.e., supply price (of any domestic and import sources).

4.2. The Process Module

Process technologies are the intermediate technologies of the system. They use input products to produce intermediate or final products of the system. This way, they basically transform a product to another one or ones.

The majority of the technologies in this module are responsible for producing intermediate sector outputs. Therefore, these are termed intermediate technologies. Other technologies that are directly linked to demands are termed demand technologies and are used to produce final products. In addition, a set of technologies are defined for onsite electricity generations. Table 3 shows the three categorized process technologies, which are mutually exclusive: The technologies that produce intermediate sector products, final products, and onsite electricity are called “Intermediate Technologies”, “Demand Technologies”, “Onsite Electricity Generation Technologies”, respectively.

Table 3. Process Technologies

Process Technologies
Intermediate Technologies
Demand Technologies
Onsite Electricity Generation Technologies

Capacity, investment, and activity of the technologies are the main decision variables associated with each of the process technologies. Typical units are displayed in tonne/year and PJ/year (for onsite electricity generation technologies). Capacity level is a cumulative variable that grows with new investments and decreases when the lifetime of any investment is over. New investment on a technology is generated based on several parameters, such as unit investment and operational costs, lifetime, annual production limitations, input requirement per unit activity and related fuel expenses, output generation level per unit activity.

Activity level is determined based on the capacity level and annual availability of the capacity. Technology activity cannot exceed its available capacity and availability of the capacity is determined by the availability factor, which basically determines the fraction of the year when the capacity is available to operate. In a standard ISEEM model, the availability factor is assumed to be 1 for all technologies. In other words, if there is no additional information specified that would suggest otherwise, the framework would consider that technological capacity was 100% available to operate. Since most of the production lines cannot be easily started/shutdown/restarted, but instead tend to be run at full capacity almost all of the time, this assumption is considered reasonable.

The following are the key input parameters of process technologies in an ISEEM model. The applications and impacts of these parameters in the ISEEM relationships will be discussed in the following subsections in detail.

- $aeei$: autonomous energy efficiency improvement of the region.
- af: annual availability factor of the technology,
- $bound\_x\_lower/bound\_x\_fix/bound\_x\_upper$: annual bounds on capacity/activity/investment: lower bound, fixed bound, and upper bound,
- $decayt/growtht$: maximum decay/growth rate of capacity between consecutive periods,
- $discount$: discount rate. This parameter is used to discount system costs.
- $emisact$: level of emission emitted per unit of technology activity,
- $fixom$: fixed operation and maintenance cost per unit of capacity,
- $inpent$: level of input requirement per unit of technology activity,
- $invcost$: investment cost per unit of new capacity addition,
- $life$: useful lifetime of the technology,

- $outent$: level of output generation per unit of technology activity,
- $resid$: existing (residual) capacity. This capacity only includes the capacities that were invested prior to the start of the planning horizon.
- $varom$: variable operation and maintenance cost per unit of activity.
- $unit$: unit conversion factor. This parameter is associated with demand technologies to do unit conversion between technology activity and demand (if demand and activity units are different).

4.3. **The Trading Module**

Trading module is used to represent the product trading relationships among the countries or regions. The active regions of the framework are linked to each other via import and export relationships. Different from the other modules, this module's relationships are built over regions (other model relations are mostly defined over technologies). Active regions create the backbone of the trading module. However, a static region representation is also used to display the relationships with the rest of the world (i.e., a collection of the regions other than the active regions).

Import of a region is basically produced in other regions and is called as export from those regions to the importing region. In other words, imports and exports of the framework are also produced in the system and they are parts of the regional productions. The production for import is included in the total production level of the exporting country.

Import and export levels of the regions are the main decision variables of the framework associated with the trading module. Thus, import level and export level of regions are to be determined for each period (e.g., on the annual basis). Typical units are displayed in tonne/year. A transportation cost is applied per unit of imported product on the basis of per unit of transport distance. It is also feasible to apply regional tariff rates on both import and export decisions in the module.

Based on the cost minimization objective, the optimization procedure determines the production, import, and export levels of the regions. If it is cost effective for a region to satisfy its demand with imports from another region or regions, the regional production may be cut down or declined and import share may be increased.

Key input parameters of trading module in an ISEEM model are summarized in the following. The applications and impacts of these parameters in the ISEEM relationships will be further discussed in the following subsections in detail.

- $bound\_x\_lower/bound\_x\_fix/bound\_x\_upper$: annual bounds on import/export; lower bound, fixed bound, and upper bound,
- $decayx/growthx$: maximum decay/growth rate of import/export between consecutive periods,
- $transportcost$: transportation cost to transfer per tonne of a product per unit distance,

- $tariffx$: tariff rates applied on import/export of a region,
- $emistrade$: level of emission emitted per unit of trading activity (i.e., shipping).

4.4. Environmental Module

Environmental module represents the GHG emissions due to industry activities. The objective function considers environmental costs like penalties or taxes. These costs can be applied as a cost of each ton of global, regional, national, or sectoral emission or a cost of each ton of excess emissions (emissions, which go beyond determined emission levels, are considered as excess emissions). Policy measures dedicated to environmental impacts can affect the optimization process and change fuel and/or process policies (e.g., shift from Basic Oxygen Furnace production to Electric Arc Furnace production in steel sector). The possible emissions scenario applications, as considered in the model, are:

- Emissions reductions (in the form of a limitation constraint on emissions at global, regional, national, or sectoral scales);
- Carbon costs (in the form of a cost application on total or individual sector system cost);

5. Mathematical Formulation of the ISEEM Modeling Framework

In this section, functional expressions and the sets and variables on which the functions are structured are defined in detail.

Basic definitions for optimization problem formulation:

Optimization programming: The optimization programming is an analysis technique for minimization (or maximization) of an objective function given a set of constraints.

Linear programming: The linear programming is a type of optimization programming in which all the functional expressions (defining the objective function and the constraints) are linear functions of the decision variables (e.g., investment, capacity, and supply).

Decision variable: The decision variables represent the (unknown) decisions to be made by the model.

Objective function: Every optimization program has an objective. The objective function is the definition of the criterion to be minimized or maximized (e.g. minimization of cost, maximization of profit).

Constraints: Every optimization program has constraints limiting the range of possible values for the decision variables (e.g., available capacities).

5.1. **Sets**

The use of sets enables ISEEM framework to define each element (e.g. technology, raw material, energy source, demand, emission) in the system. Variables and constraints are structured over the predefined sets displayed in Table 4. For example, investment variable is defined for each process technology for each period. Thus, each technology defined as a member of the set “p” should have an associated investment variable at each period. A similar structure applies -to constraints. A constraint, which is defined for the set “s”, should be only valid for the technologies associated with this set.

From this point of view, every variable and relationship in the ISSEM framework is defined over a set or a group of sets. Those sets are formed based on common features. Each element in the set must satisfy the requirements indicated by the related relationships or constraints.

Table 4. Sets of the ISEEM Modeling Framework

Set Abbreviation	Description
m	Any technology of the model
s	Supply Technology
s_i	Import Technology
s_d	Domestic Technology
p	Process Technology
p_i	Intermediate Technology
p_e	Onsite Electricity Generation Technology
p_d	Demand Technology
e	Input source (energy sources or raw materials)
dm	Demand service
v	Emission type
t	Time period
w	Any region of the model
r	Trading region

5.2. **Decision Variables**

System variables are defined according to the modules of the framework and each module has a different variable structure. As mentioned earlier, supply technologies only have activity variables. These variables define the level of supply when the supply technology operates. Thus, the only variable associated with supply module is the activity variable. On the other hand, process technologies have investment, capacity, and activity variables. Investment variable defines the level of the investment realized in the period, capacity variable defines the total capacity of the technology, and activity variable defines the capacity which is in operation. Thus, the process module has three decision variables associated with it. Trading module is different from the supply and process modules. The import and export variables are defined over regions and describe the levels of import and export between regions. Table 5 shows all the decision variables of the ISEEM modeling framework.

Table 5. Decision Variables of the ISEEM Modeling Framework

Variable	**Description**
$act(m,r,t)$	Activity Level of Technology m in region r and period t
$inv(p,r,t)$	Investment level of Process Technology p in region r and period t
$cap(p,r,t)$	Capacity Level of Process Technology p in region r and period t
$import(r,w,t)$	Import Level of Region r from region w at period t
$export(r,w,t)$	Export Level of Region r to region w at period t
$emis(v,r,t)$	Emission Level of Emitter v in region r and period t
$emis\_t(v,r,t)$	Emission Level of Emitter v due to import of region r at period t

5.3. Functional Forms

The ISEEM framework structure is primarily formed by the industry sector constraints covering production, trading, energy, and environment relations. The objective function of the system is the minimization of the total discounted cost aggregated over all periods. Most of the relations are applied over technology and region sets. A relation which is specific to a set or sets is applied to each technology or region in the set or sets. Therefore, total number of the constraints in the model is simply related with the total number of technologies and regions. On the other hand, there are a few other relations defined over energy and environment sets.

5.3.1. Total System Cost

The objective function of an ISEEM model is the minimization of the total discounted cost of the system defined for the industry. This total cost is the cumulative sum of the annualized discounted costs of each region across a predefined period of time. The objective function of an ISEEM model is as follows.

$$min \quad totalcost = \sum_{t} \sum_{r} dcost(r,t)$$

Where

$totalcost$ is the total discounted system cost.
$dcost(r,t)$ is the discounted cost of region r at time period t,

The discounted cost of each region includes the primary cost items related with the region such as supply costs, investment costs, operational costs, trading costs, and environmental costs. All the cost items other than investment costs are annual costs, so none of them needs to be annualized. However, investment cost needs to be annualized. Thus, each investment item is initially annualized, then summed.

Supply cost is the summation of all the expenses of supplying raw materials and energy sources to region r at each period and operational costs include all fixed and variable operation and maintenance costs. Trading costs, on the other hand, is the net cost of import and export of the final product in region r at period t. In addition, environmental costs are designed to represent possible negative environmental impacts on system costs.

There are five major categories for system costs: (i) supply costs, (ii) investment costs, (iii) operational costs, (iv) trading costs, and (v) environmental cost. Besides discounted costs, undiscounted costs are also reported for accounting purposes. Total undiscounted and discounted costs are discussed in detail in the following subsections.

i. ***Total Undiscounted Costs*:**

This aggregate cost item is for tracking the total undiscounted cost of region r at period t. In this relation, supply, investment, operational, trading, and environmental costs are summed in undiscounted forms.

$$\begin{aligned} ucost(r,t) = {} & usupplycost(r,t) + uinvcost(r,t) + uomcost(r,t) + utradecost(r,t) \\ & + uenvcost(r,t) \end{aligned}$$

Where

$ucost(r,t)$ is the total undiscounted cost of region r at period t,
$usupplycost(r,t)$ is the total undiscounted supply costs of region r at period t,
$uinvcost(r,t)$ is the total undiscounted investment cost of region r at period t,
$uomcost(r,t)$ is the total undiscounted operational cost of region r at period t,
$utradecost(r,t)$ is the total undiscounted trading cost of region r at period t,
$uenvcost(r,t)$is the total undiscounted environmental cost of region r at period t.

ii. ***Total Discounted Cost*:**

Total discounted costs of each region at each period are deployed in the objective function. The undiscounted costs discussed in the above section are simply discounted to the initial year of the planning horizon. Discount process works in two steps: (i) costs are discounted within the period, (ii) and then the costs, which are already discounted to the beginning of the period, are rediscounted to the initial year. Details of the discount process are given in below sections.

$$\begin{aligned} dcost(r,t) = {} & dsupplycost(r,t) + dinvcost(r,t) + domcost(r,t) + dtradecost(r,t) \\ & + denvcost(r,t) \end{aligned}$$

Where

$dcost(r,t)$ is total discounted cost of region r at period t,
$dsupplycost(r,t)$ is the total discounted supply cost of region r at period t,
$dinvcost(r,t)$ is the total discounted investment cost of region r at period t,
$domcost(r,t)$ is the total discounted operational cost of region r at period t,
$dtradecost(r,t)$ is the total discounted trading cost of region r at period t,
$uenvcost(r,t)$ is the total discounted environmental cost of region r at period t.

5.3.1.1. Total Supply Cost

The total supply cost includes all cost items related with the energy source and raw material supply.

i. *Total Undiscounted Supply Cost:*

This cost item is for tracking the total undiscounted supply cost of region r at period t. It is a function of technology activities, $act(m,r,t)$ and each supply technology is associated with a unit supply cost each time they activate. Then, the supply costs of all technologies are summed over the supply technology set, s. The function also includes a parameter to represent the possible subsidies that may be applied on raw material or energy costs. In a standard ISEEM model, these parameters are taken zero. However, they may constitute an interesting research area in scenario applications.

$$usupplycost(r,t) = \sum_{m \in s} supcost(m,r,t) * \left(1 - subsidy(m,r,t)\right) * act(m,r,t)$$

Where

$act(m,r,t)$ is the activity level of technology m in region r and period t,
$subsidy(m,r,t)$ is the rate of subsidy applied on supply cost of technology $m \in s$ in region r at period t,
$supcost(m,r,t)$ is the unit supply cost of technology $m \in s$ in region r at period t,
$usupplycost(r,t)$ is the total undiscounted supply cost of region r at period t.

ii. *Total Discounted Supply Cost:*

Discounted supply cost is the properly discounted form of undiscounted supply costs of the system, discussed in above section. The only difference is the implementation of discount factor, $df(t)$.

$$dsupplycost(r,t) = df(t) * usupplycost(r,t)$$

Where

$$df(t) = \sum_{y=1}^{nyrp} (1 + discount)^{-(y-1)}$$

$$* (1 + discount)^{-(nyrp*(t-1))}$$

Where

$df(t)$ is the discount factor,
$discount$ is the general discount rate,
$dsupplycost(r, t)$ is the total discounted supply cost of region r at period t,
$nyrp$ is the number of years per period,
$usupplycost(r, t)$ is the total undiscounted supply cost of region r at period t.

5.3.1.2. Total Investment Cost

Investment cost is different from the other expenses of the framework. This cost is paid once at the period, in which the investment is realized. Thus, it needs to be annualized initially based on the lifetime of the technology.

The investment cost of region r and period t is spread over the lifetime of the technology by applying a capital recovery factor. Capital recovery factor (CRF) is used to convert a present value into a stream of equal annual payments over a specified time, at a specified discount rate. It is calculated as a product of technology discount rate and lifetime. Below is the typical formula:

$$CRF = \frac{i}{1 - (1 + i)^{-n}}$$

Where i is the discount rate and n is the number of years.

The general capital recovery factor formula is applied to ISEEM framework as follows. In the framework, each technology has its capital recovery factor depending on its lifetime.

$$crf(m) = \frac{discount}{1 - (1 + discount)^{-life(m)}}$$

Where

$crf(m)$ is the capital recovery factor of technology m,
$discount$ is the general discount rate,
$life(m)$ is the lifetime of technology m.

i. ***Total Undiscounted Investment Cost*:**

The total investment cost includes different cost items associated with the new capacity investments that are realized in different time periods; (1) costs associated with the residual capacity, which is installed before the initial year of the planning horizon, but still alive in the current period, (2) costs associated with the investments realized in the current period and also in the previous periods (but still available in the current period).

Costs of residual capacity and the new investments are treated differently. Residual capacities are exogenously determined and placed into the model. It is assumed that if they are available in the current period, their annual payments for investment are on as well (since the investment cost is spread over the lifetime of the technology).

The philosophy is same for the new capacity additions (new investments). New capacity additions of the previous periods are the capacities that become active in the past periods, but still available in the current period. Thus, the availability of those investments at period t should be initially tracked. Since the investment cost is annualized according to the lifetime of the technology, there should be no associated cost when its lifetime is over. Then, once all the new investments of technology m that are still available at period t are determined, they are summed to find the total new investment cost of that period.

Whether a new technology investment is alive or not in a period depends on its lifetime and the period in which the investment is occurred. $(t - u_m), u_m = max\{0, t - life\ (m)/nyrp\}$ gives the interval for investments of technology m that are still available at period t. This interval also includes the new investments realized in the current period. This way, the retired capacity additions of technology m at the previous periods are not included in the period t's total capacity.

$$uinvcost(r,t) = \sum_{m} anninvcost(m,r,t) * resid(m,r,t)$$
$$+ \sum_{m} \sum_{i=u_m}^{t} anninvcost(m,r,i) * inv(m,r,i)$$

Where

$anninvcost(m,r,t)$ is the annualized investment cost of technology m in region r at period t,
$inv(m,r,t)$ is the investment level of technology m in region r and period t,
$resid(m,r,t)$ is the level of residual capacity of technology m in region r at period t,
$uinvcost(r,t)$ is the total undiscounted investment cost of region r at period t.

Annualization of unit investment costs is calculated using the capital recovery factor and unit investment cost:

$$anninvcost(m, r, t) = crf(m) * invcost(m, r, t)$$

Where

$\mathrm{anninvcost(m, r, t)}$ is the annualized investment cost of technology m in region r at period t,
$crf(m)$ is the capital recovery factor of technology m,
$\mathrm{invcost(m, r, t)}$ is unit investment cost of technology m in region r at period t.

ii. *Total Discounted Investment Cost (Annualized):*

Discounted investment cost is the summation of annualized and discounted investment costs of the system technologies in region r at period t. An aggregate annualization/discount parameter, $crfdisc(m, t)$, is used for annualization and discount of the investment cost. Annualization is calculated using the capital recovery factor. Discount, on the other hand, is calculated based on the basic present value formula, which is discussed earlier in $df(t)$ case. Thus, the aggregate formula is as follows.

$$crfdisc(m, t) = crf(m) * (1 + discount)^{-(nyrp*(t-1))}$$

Where

$crf(m)$ is the capital recovery factor of technology m,
$crfdisc(m, t)$ is aggregate annualization/discount parameter of technology m at period t,
$discount$ is the general discount rate,
$nyrp$ is the number of years per period.

Then, the discounted investment cost of technology m, $discinvcost$, is calculated as follows.

$$discinvcost(m, r, t) = crfdisc(m, t) * invcost(m, r, t)$$

Where

$discinvcost(m, r, t)$ is the discounted investment cost of technology m in region r at period t,
$crfdisc(m, t)$ is aggregate annualization/discount parameter of technology m at period t,
$\mathrm{invcost(m, r, t)}$ is unit investment cost of technology m in region r at period t.

The total discounted investment cost of region r at period t is, then, summed over the technology set m.

$$dinvcost(r,t) = \sum_{m\in p} discinvcost(m,r,t) * (resid(m,r,t,) + inv(m,r,t))$$

Where

$dinvcost(r,t)$ is the total discounted investment cost of region r at period t,
$discinvcost(m,r,t)$ is the discounted investment cost of technology m in region r at period t,
$inv(m,r,t)$ is the investment level of technology m in region r and period t,
$resid(m,r,t)$ is the level of residual capacity of technology m in region r at period t.

5.3.1.3. Total Operational Cost

This cost item includes all fixed and variable operational and maintenance costs. Fixed costs (e.g. loan credits) are calculated over technology capacities, while variable costs (e.g. labor costs) are calculated over technology activities. Therefore, the fixed costs are realized if there is an available capacity on hand. It is not necessarily be active. On the other hand, to apply variable costs, active (operating) capacities are needed.

i. *Total Undiscounted Operational Cost:*

This cost is for tracking the undiscounted operational costs of region r at period t. The first item in the function gives the total fixed operational cost aggregated over all technologies. The second item gives the total variable operational cost aggregated over all technologies.

$$uomcost(r,t) = \sum_{m\in p} fixcost(m,r,t) * cap(m,r,t) + \sum_{m\in p} varcost(m,r,t) * act(m,t)$$

Where

$act(m,r,t)$ is the activity level of technology m in region r and period t,
$cap(m,r,t)$ is the capacity level of technology m in region r and period t,
$fixcost(m,r,t)$ is the fixed operation cost per unit capacity of technology m in region r at period t,
$varcost(m,r,t)$ is the variable operation and maintenance cost per unit activity of technology m in region r at period t.
$uomcost(r,t)$ is the total undiscounted operational cost of region r at period t.

ii. *Total Discounted Operational Cost*:

Discounted operational cost is the properly discounted form of undiscounted supply costs of the system, discussed in above section. The only difference is the implementation of discount factor, $df(t)$. Discount factor is the same parameter that is used to discount supply costs.

$$domcost(r,t) = df(t) * uomcost(r,t)$$

Where

$df(t)$ is the discount factor,
$domcost(r,t)$ is the total discounted operational cost of region r at period t,
$uomcost(r,t)$ is the total undiscounted operational cost of region r at period t.

5.3.1.4. Total Trading Cost

This cost item is an aggregation of the costs related with the trading import costs, export costs, transportation costs, and tariffs. Import and export costs of active regions are calculated endogenously in the framework. Import and export costs of static region, on the other hand, are provided exogenously (there is no production sector defined for the static region). Static region is primarily needed in the model calibration phase.

Import cost of an active region is the summation of production cost of the product in its origin region, transportation cost to the region, and tariffs applied by either the exporting or importing region, or both. Tariffs can be applied on a product in three different ways; (i) only export tax, which is the tax the origin region applies before it is imported, (ii) only import tax, which is the tax the importing region applies before it enters, (iii) import plus export tax; both regions apply.)

A region can import the same product from various other regions. However, in this case, the product has different import costs depending on the region the product comes from. Export costs, on the other hand, in fact are the revenue to the system, thus, they are applied with minus signs.

The static region, represented as r' and exogenous import and export costs applied the products coming from there.

i. *Total Undiscounted Trading Cost*:

The undiscounted trading cost of the system is a cost item constructed to track the discounted trading costs of region r at period t. The first item in the relationship gives the total import cost from dynamic regions. The second item is for import cost from static region. The third and fourth items represent the revenues from exports; both dynamic and static regions. The framework only includes the cost items. Thus, since the transportation cost or tariffs that might come from exported products are considered as profits, they are not included as a part of the export relations.

$$utradecost(r,t) = \sum_{w, where\ w \neq r'\ and\ w \neq r} prodcost(r,w,t)$$

$$+\big(transportcost(r,w,t) + tariffi(r,w,t) + tariffe(r,w,t)\big) * import(r,w,t)$$

$$+importcost(r, r', t) * import(r, r', t)$$

$$- \sum_{w, where\ w \neq r'\ and\ w \neq r} prodcost(w, r, t) - exportcost(r', r, t) * export(r', r, t)$$

Where

$export(r, w, t)$ is the export level of region r to region w at period t,
$exportcost(r', r, t)$ is the exogenous export cost defined by the user for region r at period t for the imports from or exports to static region, r',
$import(r, w, t)$ is the import level of region r from region w at period t,
$importcost(r, r', t)$ is the exogenous import cost defined by the user for region r at period t for the imports from or exports to static region, r',
$tariffe(r, w, t)$ is the tariffs implied on the product on original region w (before being imported to region r) at period t,
$tariffi(r, w, t)$ is the tariffs implied on the product on import region r,
$transportcost(r, w, t)$ is the cost of transferring per tonne of the product from region w to region r at period t,
$utradecost(r, t)$ is a total undiscounted trading cost of region r at period t,

$prodcost(r, w, t)$ is the total production cost of products that region r imported from region w at period t. Formulation is as follows.

$$prodcost(r, w, t) = usupplycost(r, t) + uinvcost(r, t) + uomcost(r, t) + uenvcost(r, t)$$

Where

$usupplycost(r, t)$ is a total undiscounted supply cost of region r at period t,
$uinvcost(r, t)$ is a total undiscounted investment cost of region r at period t,
$uomcost(r, t)$ is a total undiscounted operational cost of region r at period t,
$uenvcost(r, t)$is a total undiscounted environmental cost of region r at period t.

ii. *Total Discounted Trading Cost*:

Discounted trading cost is the properly discounted form of undiscounted operational costs of the system technologies. The cost structure remains similar to the undiscounted cost discussed in above section. The only difference is the implementation of discount factor, $df(t)$. Discount factor is the same parameter that is used to discount supply costs.

$$dtradecost(r, t) = df(t) * utradecost(r, t)$$

Where

$df(t)$ is the discount factor,
$dtradecost(r,t)$ is the total discounted trading cost of region r at period t,
$utradecost(r,t)$ is the total undiscounted trading cost of region r at period t.

5.3.1.5. Total Environmental Cost

Environmental costs represent all environmental penalties, fees, and costs related with the various undesirable emissions and other negative impacts of sectoral production activities to the system. In addition, the framework also considers maritime emissions resulted from transportation of product between regions. If there is a cost related with the emissions due to trading, it is represented in the framework as well. In a standard ISEEM model, all environmental costs are assumed to be zero in our study. However, they constitute an interesting future research area in scenario applications.

i. ***Total Undiscounted Environmental Costs:***

$$uenvcost(r,t) = uenvcost\_p(r,t) + uenvcost\_t(r,t)$$

$$uenvcost\_p(r,t) = \sum_{v} envcost(v,r,t) * emis(v,r,t)$$

$$uenvcost\_t(r,t) = envtrade(r,t) * emis\_t(r,t)$$

Where

$emis(v,r,t)$ is the emission level of emitter v in region r and period t,
$emis\_t(v,r,t)$ is the emission level of emitter v due to import of region r at period t,
$envcost(v,r,t)$ is the unit emission cost per emission item v due to production at region r at period t,
$envtrade(v,t)$ is the unit emission cost due to trading of region r at period t.
$uenvcost(r,t)$is the total undiscounted environmental cost of region r at period t.
$uenvcost\_p(r,t)$ is the total undiscounted environmental costs (due to production) of region r at period t,
$uenvcost\_t(r,t)$ is the total undiscounted environmental cost (due to trading) of region r at period t.

ii. ***Total Discounted Environmental Costs:***

$$denvcost(r,t) = df(t) * uenvcost(r,t)$$

Where

$df(t)$ is the discount factor,
$denvcost(r,t)$ is the total discounted environmental cost of region r at period t,
$uenvcost(r,t)$ is the total undiscounted environmental cost of region r at period t.

5.3.2. Balance Constraint

These constraints require that total usage of any raw material or energy source cannot exceed its total supply. Thus, in the developed framework, each raw material and energy source is related with two sets; (i) set of the technologies supplying and producing the raw material or energy source, and (ii) set of the technologies exporting and consuming the raw material or energy source. The balance relationship is built between those two sets.

The technologies supplying and producing the raw material or energy source are represented at the left hand side of the constraint. The supply comes from supply technologies while the production comes from process technologies. The technologies exporting and consuming the raw material or energy source, on the other hand, are represented at the right hand side of the constraint. Consuming technologies can be any type of system technology. However, how and how much they consume the energy source depends on the associated input requirement. Gross amount of some raw materials (e.g. crude iron ore) cannot perform in the same way. For example, iron content of crude iron ore varies according to where the crude iron ore extracted. The iron content of China crude iron ore is approximately 31%, compared to approximately 63% of the U.S. This shows that a unit of crude iron ore from China satisfies half of what the crude iron ore from the U.S. does. To reflect this share in the framework, a content parameter is used, $content$.

- m_e: the set of the technologies supplying and producing the product e,
- k_e: the set of the technologies exporting and consuming the product e.

$$\sum_{m \in m_e} outent(m,e,r,t) * act(m,r,t)$$
$$\geq \sum_{m \in k_e} (inpent(m,e,r,t)/(1 - content(m,r,t))) * act(m,r,t)$$

The ISEEM framework has the ability to apply autonomous efficiency improvement to the calibration (or base) year technologies. If desired, energy consumptions of those technologies are improved each year with an autonomous improvement parameter, which is specific to each region of the framework, but independent from the technology or period. $aeei(r)$ defines general the autonomous energy efficiency improvement parameter of the region r, and the input parameter is calculated as follows.

$$inpent(m,e,r,t) = inpent(m,e,r,t') * \left(1 - aeei(r)\right)^{(t-t')},$$

$$where\ t'represents\ the\ calibration\ year$$

Where

$act(m,r,t)$ is the activity level of technology m in region r and period t,
$inpent(m,e,r,t)$ is the level of input requirement (product e) per unit activity of technology m in region r at period t
$outent(m,t)$ is the level of output generation (product e) per unit activity of technology m in region r at period t,
$content(m,r,t)$ is the rate of impurity in the input. If there is no purity or content issue for the raw material, this parameter is assumed 0. Thus, in a standard ISEEM model, the default value for content rates is 0 unless specified otherwise.

5.3.3. Periodic Capacity Constraint

This relationship ensures that period capacity is equal to the residual capacity (which is installed before the start of the planning horizon, but still alive in the current period) plus the new capacity additions of previous periods (but still exists in the current period) and the current period. Residual capacities are exogenously determined and placed into the model. On the other hand, new capacity additions of the previous periods are the capacities that become operational in the past periods and are still operational in the current period. In addition, earlier capacity additions (investments) should be removed from the total capacity when the associated lifetimes are over. Whether an investment is alive or not in period t depends on the lifetime of the technology and the period in which the investment is occurred. From this point of view, $(t - u_m\ ), u_m = ma\,x\left\{0, t - \ lifetime\ of\ technology \frac{m}{nyrsper}\right\}$ gives the interval for available investments of technology m at period t.

$$cap(m,r,t) = resid(m,r,t) + \sum_{i=u_m}^{t} inv(m,r,i)$$

Where

$cap(m,r,t)$ is the capacity level of technology m in region r and period t,
$inv(m,r,i)$ is the investment level of technology m in region r and period i,
$resid(m,r,t)$ is the level of residual capacity of technology m in region r at period t.

5.3.4. Activity - Capacity Relation Constraint

These relationships ensure that activity level of any process technology cannot exceed its available capacity. Available capacity is a product of annual availability factor of the capacity and capacity level itself.

$$act(m,r,t) \leq af(m,r,t) * cap(m,r,t), m \in p$$

Where

$act(m,r,t)$ is the activity level of technology m in region r and period t,
$af(m,r,t)$ is the annual availability factor of technology m $\in p$ in region r at period t,
$cap(m,r,t)$ is the capacity level of technology m in region r and period t,

5.3.5. Cumulative supply limit

These constraints are used to apply cumulative supply limitations such as reserve capacity limitations on domestic resources or contract limitations on imported resources. They are only applicable to supply technologies.

$$\sum_{t} act(m,r,t) * nyrp \leq cum(m,r), m \in s$$

Where

$act(m,r,t)$ is the activity level of technology m in region r and period t,
$cum(m,r)$ is the cumulative capacity limitation on supply technology $m, m \in s$ in region r,
$nyrp$ is the number of years in a period.

5.3.6. Demand Constraint

These constraints ensure that there is always sufficient capacity to meet the demand requirements. Total activities of technologies serving a specified demand should be greater than or equal to demand service itself.

- $m_{dm}(m)$: the set of technologies serving the demand service dm.

$$\sum_{m \in m_{dm}} outent(m, dm, r, t) * unit(m) * act(m, r, t) + \sum_{w, where\ w \neq r} import(r, w, t) \geq demand(dm, r, t)$$

Where

$act(m, r, t)$ is the activity level of technology m in region r and period t,
$outent(m, dm, r, t)$ is the level of demand service dm satisfied per unit activity of technology m in region r at period t,
$demand(dm, r, t)$ is the level of demand service dm that has to be satisfied in region r at period t,
$import(r, w, t)$ is the import level of region r from region w at period t,
$unit(m)$ is the unit conversion factor associated with demand technologies for unit conversion between technology activity and demand (if demand and activity units are different).

5.3.7. Export Satisfaction Constraint

These constraints ensure that total export from a region cannot exceed the portion of the regional production which is assigned for exporting purposes. Total activities of technologies serving for the products that will be exported should be greater than or equal to total export of the region itself.

- $m_{dm-ex}(m)$: set of technologies serving the export of final product $dm - ex$.

$$\sum_{m \in m_{dm-ex}} outent(m, dm - ex, r, t) * unit(m) * act(m, r, t) \geq \sum_{w, where\ w \neq r} export(r, w, t)$$

Where

$act(m, r, t)$ is the activity level of technology m in region r and period t,
$export(r, w, t)$ is the export level of region r to region w at period t,
$outent(m, dm - ex, r, t)$ is the level of export $dm - ex$ produced per unit activity of technology m in region r at period t,
$unit(m)$ is the unit conversion factor.

5.3.8. Trade Constraint

These constraints match up the trade in final products between two regions. The constraint indicates that import from a region should be equal to export of that region to importing region.

$$import(r,w,t) = export(w,r,t), where\ w \neq r\ and\ w \neq r'$$

Where

$export(r,w,t)$ is the export level of region r to region w at period t,
$import(r,w,t)$ is the import level of region r from region w at period t.

5.3.9. Emission Constraints

Functional relationships representing emission activities can be separated into two groups: (i) emissions from industry production, (ii) emissions from trading.

i. *Emissions from Production*:

These relations track the level of emissions emitted through the activity of technology m.

$$\sum_{m} emisact(v,m) * act(m,r,t) = emis(v,r,t)$$

Where

$act(m,r,t)$ is the activity level of technology m in region r and period t,
$emis(v,r,t)$ is the emission level of emitter v in region r and period t,
$emisact(v,m)$ is the level of emission type v emitted per unit activity of technology m.

ii. *Emissions from Trading*:

These relations track the level of emissions emitted through trading of region r. It is assumed that a region is only responsible for emissions due to its import.

$$\sum_{w, where\ w \neq r} emistrade(v) * import(r,w,t) = emis\_t(v,r,t)$$

Where

$emis\_t(v,r,t)$ is the emission level of emitter v due to import of region r at period t,
$emistrade(v)$ is the level of emission type v emitted per unit import of final product,
$import(r,w,t)$ is the import level of region r from region w at period t.

iii. ***Total Emissions*****:**

These relations track the level of total emissions emitted per region per period and the global emissions emitted per period.

$$totalemis(r,t) = emis(v,r,t) + emis\_t(v,r,t)$$

$$globalemis(t) = \sum_{r} totalemis(r,t)$$

Where

$emis(v,r,t)$ is the emission level of emitter v in region r and period t,
$emis\_t(v,r,t)$ is the emission level of emitter v due to import of region r at period t,
$totalemis(r,t)$ is the level of total emissions emitted in region r at period t,
$globalemis(t)$ is the level of global emissions emitted from all regions of the system at period t.

5.3.10. Supply Decay and Growth Constraints

These constraints ensure that decay or growth of supply from a particular supply technology between two consecutive periods is limited by decay and growth rate parameters. These relationships prevent the supply of any supply technology to decrease/increase below/above of a certain percentage of the previous period's supply.

$$act(m,r,t+1) \geq act(m,r,t) * decayr(m,r,t+1)^{nyrp}, m \in s$$

$$act(m,r,t+1) \leq act(m,r,t) * growthr(m,r,t+1)^{nyrp}, m \in s$$

Where

$act(m,r,t)$ is the activity level of technology m in region r and period t,
$decayr(m,r,t)$ is the maximum annual decay rate of technology m's supply level at region r between period t and period $t+1$,

$growthr(\mathrm{m}, r, \mathrm{t})$ is the maximum annual growth rate of technology m’s supply level at region r between period t and period $t+1$.

5.3.11. Capacity Decay and Growth Constraints

These constraints ensure that decay or growth of the capacity of the any technology between two consecutive periods is limited by decay and growth rate parameters. These relationships prevent capacity of any technology to decrease/increase below/above a certain percentage of the previous period’s capacity.

$$cap(m,r,t+1) \geq cap(m,r,t) * decayt(m,r,t+1)^{nyrp}, m \in p$$

$$cap(m,r,t+1) \leq cap(m,r,t) * growtht(m,r,t+1)^{nyrp}, m \in p$$

Where

$cap(m,r,t)$ is the capacity level of technology m in region r and period t,
$decayt(m,r,t)$ is the maximum annual decay rate of technology m’s capacity at region r between period t and period $t+1$,
$growtht(\mathrm{m}, r, \mathrm{t})$ is the maximum annual decay and growth rate of technology m’s capacity at region r between period t and period $t+1$.

5.3.12. Trade Decay and Growth Constraints

These constraints ensure that the decay or growth rate of the import/export of any region between two consecutive periods is limited by a specific parameter range for decay or growth rate. These relationships prevent import/export of any region to decrease/increase below/above a certain percentage of the previous period’s import/export.

$$import(m,r,t+1) \geq import(m,r,t) * decayi(m,r,t+1)^{nyrp}$$

$$export(m,r,t+1) \geq export(m,r,t) * decaye(m,r,t+1)^{nyrp}$$

$$import(m,r,t+1) \leq import(m,r,t) * growthi(m,r,t+1)^{nyrp}$$

$$export(m,r,t+1) \leq export(m,r,t) * growthe(m,r,t+1)^{nyrp}$$

Where

$decayi(m, r, t)$ is the maximum annual decay rate of region r's import between period t and period $t + 1$,
$decaye(m, r, t)$ is the maximum annual decay rate of region r's export between period t and period $t + 1$,
$export(r, w, t)$ is the export level of region r to region w at period t,
$growthe(\mathrm{m}, r, \mathrm{t})$ is the maximum annual growth rate of region r's export between period t and period $t + 1$.
$growthi(\mathrm{m}, r, \mathrm{t})$ is the maximum annual growth rate of region r's import between period t and period $t + 1$,
$import(r, w, t)$ is the import level of region r from region w at period t.

5.3.13. Periodic Bound Constraints

Periodic limitations are used to restrict the levels of activity, capacity, or investment a technology per period. In the representations below, $r\_x(m, r, t)$ represents activity/capacity/investment (the one that is applicable) of technology m in region r at period t. x represents the set of technologies that activity, capacity, or investment variables are applicable. For example, there are no capacity and investment variables for supply technologies.

$$r\_x\ (m, r, t)\ \le bound\_x\_upper(m, r, t), m \in x$$

$$r\_x\ (m, r, t)\ = bound\_x\_fix(m, r, t), m \in x$$

$$r\_x\ (m, r, t)\ \ge bound\_x\_lower(m, r, t), m \in x$$

Where

$bound\_x\_fix(m, t)$ is a fixed bound on activity/capacity/investment of technology m in region r at period t,a
$bound\_x\_lower(m, t)$ is a lower bound on activity/capacity/investment of technology m in region r at period t,
$bound_x_upper(m, t\ )$is an upper bound on activity/capacity/investment of technology m in region r at period t.

5.3.14. Scenario Constraints

The constraints in this category are developed for the purpose of performing possible scenario analysis. They are not active in a standard ISEEM model but are implemented in scenario or sensitivity analysis.

Normally the constraints are constructed for specific technology, resource, or trade sets. The associated technology, resource, and trade sets are formed according to scenario requirements. Examples of possible scenario constraints are discussed in this subsection.

i. ***Support of a Particular Process in a Sector*:**

Production constraints are to force the production from specific process types (e.g., applying a lower bound to the production from Basic Oxygen Furnace processes in steel sector).

$$act(m', r, t) \geq \alpha(m', r, t) * \sum_{m \in (set\ of\ technologies\ producing\ the\ final\ product\ c)} act(m, r, t)$$

Where

$\alpha(m', r, t)$ is the minimum share of technology m' in total production of final product c at region r and period t.

ii. ***Restrictions on Importing from a Region*:**

Constraints are to restrict the import of the final product from a specific region at period t.

$$import(r, r', t) \leq \partial(r, r', t) * \sum_{w} import(r, w, t)$$

Where

$\partial(r, r', t)$ is the maximum share of importing from region r' in total import of region r at period t.

iii.*Restrictions on Exporting in a Region:*

Constraints are to restrict the share of export in the total production of region r at period t.

$$\sum_{w} export(r, w, t) \leq \beta(r, t) * \sum_{m \in (set\ of\ technologies\ producing\ the\ final\ product\ c)} act(m, r, t)$$

6. Summary and Model Application

Industry Sector Energy Efficiency Model (ISEEM) is a new mathematical model developed in this project to emulate the energy systems, raw material and commodity flow, production and trading mechanisms of industrial products, and carbon trading among selected regions. Specifically, ISEEM framework is developed as a simple, flexible, bottom-up, linear optimization modeling framework that allows analysis of commodity and carbon trading between nations. The purpose of the modeling using bottom-up representation is to enable baseline and scenario analyses that consider energy efficiency measures as mitigation options, cost optimization of carbon reduction while allowing commodity and carbon trading as viable alternatives to carbon-emission reduction goals. Using this new model, we expect to develop new information and knowledge that can assist decision-making in advancing comprehensive energy strategies and carbon reduction planning for the industrial sectors.

Technically, the ISEEM modeling framework is focused on the mechanisms and relationships that would emulate any industry sector as realistically as possible, with the detail that would enable analyzing the changes in energy consumption and carbon emissions via energy efficiency and financial tools. The complex relationships of supplying and producing energy sources and raw materials are represented with technological details in the model. The ISEEM framework can be used to analyze the effects of various trading characteristics such as tariffs, import/export taxes, emissions associated with commodity trading (i.e., international shipping), which are not available for analysis using the other modeling frameworks reviewed and discussed in this report. In addition, different from the other modeling frameworks that have well-defined rigid structures or interfaces that prevent users from adding new relations (which are not defined or placed into the system in functional forms as parts of system equations) to the modeling system, ISEEM framework is designed to be an open structure that provides a compatible environment for users to build additional relations per the users' needs for or preference to analyzing various scenarios.

The ISEEM framework can be used to analyze a single or multiple industrial sectors, and provides users the ability to model one or multiple nations (or regions) depending on what the user wants to analyze (e.g., modeling for one nation with static trading relationships, or modeling over multiple nations with dynamic commodity or carbon trading relationships). Built upon bottom-up approach to include end use technologies, an ISEEM system provides a technology rich basis for estimating industrial production and trading volumes, production costs, energy dynamics, and emissions over a multi-period time horizon. Compared to existing energy modeling frameworks, the main feature of the ISEEM framework is its ability to project future commodity and carbon trading volumes among multiple regions, while seeking for the least-cost mix of technologies with the goal of carbon reduction. Since trading is directly related with production, the user is also capable of computing the increase and/or decrease in productions, energy consumptions, and emissions due to changes in trading relationships.

As ISEEM framework aims to compute supply (of raw material and energy sources) and production (of intermediate and final products) in an industrial sector while seeking for the least system cost for certain emission reduction goals in selected periods of time. Costs, availability factors, supply, capacity, investment, or activity limitations, input requirements, and unit output generation per technological activity are the main parameters driving the least cost objective. The final product produced by process technologies are used to satisfy either demand of the region, in which the final product is produced, or demands of the other regions via trading. System demands are determined outside of the model and exogenously placed to the system. Export and import levels, on the other hand, are determined endogenously. According to optimization process, if it is cost effective for a region to satisfy its demand via imports from another region or regions, the production in the specific region may be reduced and import share might be increased. However, in this case, production and export levels of the other regions may also increase simultaneously. The ISEEM model will allow users to project the outcomes from various scenarios to understand potential impacts on energy use and carbon emissions via trading offsets among selected regions or countries.

In the follow-up ISEEM modeling applications, we will apply ISEEM framework to two industrial sectors – one is iron and steel, and the other is cement sector, respectively, in three countries, i.e., The U.S., China, and India. In particular, we will model each industry sector in the three countries to include the existing and future national productions, energy consumptions, and emissions trends as well as trading relationships among these countries. The base-case and future scenarios will be defined for modeling analysis. For example, we can perform different scenarios (e.g., carbon cap such as specifying an absolute or relative carbon reduction goal, with and without commodity trading; or carbon offset via carbon trading). For each scenario with a specific emission-reduction goal, we can use the ISEEM model to investigate the outcomes and sensitivities with different emission-reduction goals under carbon caps (with and without trading), respectively.

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