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Multi-model comparison of CO_2 emissions peaking in China: Lessons from CEMF01 study

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Multi-model comparison of CO_2 emissions peaking in China: Lessons from CEMF01 study

中国能源模型论坛（CEMF）
清华大学

【编者按】随着《巴黎协定》的达成，全球应对气候变化的框架初步形成。我国正处于新的五年规划阶段，面临着来自经济增长、能源资源约束以及环境治理方面的重重考验。如何在经济发展、能源消费与环境保护之间更好地决策，如何为决策提供坚实的科学支持和指导，都是当前面临的问题。中国能源模型论坛旨在运用并比较多种不同的能源经济模型，分析适合中国国情的能源及环境目标，探讨目标实现过程中的成本、相关效益及风险问题，明确影响目标实现的主要因素。

中国能源模型论坛主题研究一（CEMF01）于 2015 年底启动，研究主题为“巴黎协议，十三五规划目标和碳排放峰值-多模型比较研究”。CEMF01 基于自上而下的 CGE 模型和自下而上的模型，包括覆盖全经济、全行业范围的，和侧重于单行业的模型。为实现研究目标，CEMF 委托国内知名模型团队开展了相应研究，包括:

- 国家信息中心团队的 SIC-CGE 模型（全行业分析）
- 中国科学院科技战略咨询研究院团队的 CAS-PIC-Macro 模型（全行业分析）
- 清华大学能源环境经济研究所团队 CHINA-MAPLE 模型（全行业分析）
- 国家信息中心团队的 SIC-IIS 模型 （钢铁行业）
- 环境保护部环境与经济政策研究中心团队的 PRCEE-TIMES-Cement 模型(水泥行业)
- 环境保护部环境与经济政策研究中心团队的 PRCEE-LEAP-Transportation 模型(交通行业)
- 国家应对气候变化战略研究和国际合作中心 NCSC-ELECTRC-TIMES 模型（电力行业）

在此基础上，CEMF 团队完成了《中国碳排放峰值的多模型比较研究（CEMF01)》，主要采用多模型比较的研究方法，在多种情景下对同类模型的排放峰值进行比较，通过建立比较平台，对不同类型模型的结果进行比较，探讨模型之间的关联性、模型情景设定的合理性，分析同类模型结果差异的主要原因，对模型参数设定的科学合理性讨论，提高各个模型的公信力。同时，通过比较和调整校准得各自模型，形成新的、更具研究透明性和可信度的中国碳排放峰值的综合研究成果，供决策部门参考。

本报告的研究工作是在 CEMF 学术委员会的指导下完成的，研究过程中，得到了来自清华大学、国家发展和改革委员会能源研究所、国家应对气候变化战略中心、国家信息中心、环保部环境与经济政策研究中心、国务院发展研究中心、复旦大学、中国矿业大学、冶金工业规划研究院、中国石油和化学工业联合会、交通部科学研究院、中国电力企业联合会、国网能源研究院、中国环境科学研究院、中国农业科学研究院等多家单位的专家学者的大力支

持，同时也离不开 CEMF 秘书处的协调工作。

CEMF 研究报告将陆续刊发 CEMF01 研究成果及各分报告的摘要版本，供读者参考。如您对本研究有咨询和建议，请联系北京市清华大学公共管理 615 室，中国能源模型论坛（100084），或发送邮件至 cemf@tsinghua.edu.cn。我们的官方网站是 www.cemf.net.cn。

TABLE OF CONTENTS

Introduction

On the annual United Nations Climate Change Conference in Paris (COP21[1], 2015), 196 nations officially agreed on cutting carbon emissions. The parties of the *Paris Accord* have committed to limit the average global temperature rise below 2℃ above pre-industrial levels and to pursue efforts to limit the temperature increase within 1.5℃. Though the Paris Agreement significantly differs from Kyoto Protocol, voluntary and unbinding, it demonstrated a broad acknowledgement of the climate change threat and even set a new, stronger target. As summarized at IPCC 5th report, the 2℃ threshold still leaves high risk to "unique and threatened systems". The most recent studies argue that the additional 0.5℃ degree makes a big difference in reducing overall climate change impact, such as extreme weather events, reductions in agricultural output, decreases in surface runoff, severe drought, growth of epidemic diseases incidence, and further widening the regional gap in global social and economic development (Huang et al., 2017)[2].

However, the sum of currently committed by participating the agreement countries intended nationally determined contributions (INDCs) is far from sufficient to achieve the temperature control goal of 2℃ (UNDP 2016), not to mention the goal of 1.5℃. China, as the largest emitter of greenhouse gases in the world (accounting for around 30% of the world total), can play a critical role in reducing global greenhouse gas emissions. Also, China is one of world regions with expected major environmental damages from climate change (see "The third national climate change assessment report", 2015, Shilu Tong et al, 2016).

The Chinese government recognizes the risk and responsibility, and has been persistently strengthening environmental targets during the recent decade. At the United Nations Climate Change Conference in 2009 (COP15), China committed to cut CO_2 emissions per unit of GDP by 40%-45% from its 2005 level by 2020. This target has been reinforced on the COP21 meetings in 2015 in Paris, with commitment to cut emissions by 60-65% per unit of GDP, to increase the share of non-fossil energy to 20%, and peak CO_2 emissions by 2030. The international commitments have been already directed for implementation in the national targets and plans.

In its *13th Five-Year Plan* (13FYP), the Chinese Government articulated ambitions to reduce emissions and foster low-carbon development, including controlling CO_2 emissions in key industries (e.g. power sector, iron & steel, building materials and chemical and petrochemical industry), promoting low-carbon development in key sectors (e.g. industry, energy, buildings and transportation), strengthening adaptability to climate change, and contributing to global climate governance (NDRC, 2016).

Implementation of the commitment to reduce emissions required plans to specify details of emissions reduction and energy development goals. In particular, the *Work Plan for Greenhouse Gas Emission Control during the 13th Five-Year Plan Period* outlined China's plan to decrease CO_2 emissions per unit of GDP by 18% by 2020, and peak CO_2 emissions in some heavy chemical industries around 2020. The document also noted China's goal of further controlling emissions of greenhouse gases other than CO_2, such as HFCs, methane, nitrous oxide, PFCs and sulfur hexafluoride. According to the document, China also aims to reduce energy consumption per unit of GDP by 15% over 2015, and cut emissions by continuously reducing coal consumption in heavily

[1] http://www.cop21paris.org/about/cop21

[2] The special issue of IPCC report on 1.5C expected in 2018 will address the difference in details.

polluted regions and cities beginning in 2017. The country hopes to increase the share of non-fossil energy sources in its energy sector, thus limiting CO_2 emissions per unit of power supplied by large power generation groups below 550g CO_2/kWh (The State Council, 2016).

The *13FYP for Energy Development* (NDRC, 2016) proposed to control both total energy consumption and energy consumption intensity. The proposal sought to fundamentally reverse the extensive growth pattern of energy consumption and reduce the share of coal in total primary energy supply to 58% or less by 2020 while increasing the combined share of non-fossil energy, natural gas and other low-carbon energy sources to 25%. On this basis, the Chinese Government issued the *Energy Production and Consumption Revolution Strategy 2016-2030 (NDRC and NEA, 2016)*, which advances further energy revolution goals:

- limit total energy consumption below 5 billion metric tons of coal equivalent by 2020, and limit total energy consumption below 6 billion metric tons of coal equivalent by 2030;
- achieve sustainable growth of renewable energy, natural gas and nuclear power use while drastically reducing high-carbon fossil energy use by 2030;
- increase the proportion of non-fossil fuel sources to 20% by 2030;
- increase the natural gas share to 15% or more by 2030;
- satisfy new energy demand mainly with clean and low-carbon energy;
- promote clean and efficient use of fossil energy, peak CO_2 emissions around 2030 and strive for the earliest possible peak;
- reduce energy consumption per unit of GDP to the current world average level;
- establish global leadership in energy science and technology.

The strategy also contains 2050 energy targets, including increasing the share of non-fossil energy to over 50%, while maintaining a stable level of energy consumption (Energy Production and Consumption Revolution Strategy, 2016-2030).

With these important steps done, still there are a lot of questions and uncertainty regarding whether the targets are feasible and will be met, whether the commitment is strong enough or unbounding, what potential and associated costs of emissions reduction is, and what will be the optimal target for reaching maximum emissions reductions without compromising the country's economic development. Reliable answers to the questions are especially important on international arena, where nations will have to confront questions like how to ensure that different countries constantly strengthen efforts in emission reduction, how to effectively evaluate contributions of each country to emission reduction, and how to determine feasible paths and policy measures suitable for the global temperature control.

A number of studies have been undertaken in China and worldwide to address greenhouse gas emission projections, potential and costs of reduction, and carbon emissions peaking pathways (Jiang et al., 2016; Wang et al., 2015; Dong et al., 2015; Grub et al. 2015; He et al., 2013; Gambhir at al. 2012). Most of them involve sophisticated modeling techniques to simulate and analyze potential pathways of long-run development of the economy and the energy sector. For example, using Integrated energy and environment Policy Assessment model for China (IPAC), the Energy Research Institute of National Development and Reform Commission have found that under certain conditions, emissions from China's energy use could peak by 2025 or even earlier on the level around 9 billion metric tons (Jiang et al., 2016). Research by Ma et al. shows that development of renewable energy coupled with improvements in energy efficiency and emission reduction technology in energy-intensive industries could promote CO_2 emission peaking and energy-intensive industrial sectors at 10-10.8 billion metric tons by 2030 (Ma et al., 2016).

The conditions of scenarios and assumptions vary from study to study, and may depend on differences of researchers' view on the same problems. Consideration and comparison of a large pool of scenarios may potentially bring more information, i.e. provide some robustness in case if results are similar, or estimate a range of uncertainty as a difference between projections. For example, Hu Xiulian (2016) collected more than 30 scenarios of several domestic and international modeling groups, and found that in those baseline scenarios, China's CO_2 emissions will peak at about 13.5-17 billion metric tons in 2040-2050. Around half of the low carbon scenarios will peak on levels 8.2-13 billion metric tons CO_2 during 2020-2030 and reduce to 5-8 billion metric tons by 2050, and the other half peak at 8.4-11 billion metric tons around 2020 and reduce to 2.5-3 billion metric tons by 2050 (Hu, 2016).

Another comparison is provided by *The third national climate change assessment report* (NCCARWC, 2015), where scenarios of CO_2 emissions in China from 2005 to 2050 have been collected from studies published after 2010. The researchers found that China's future CO_2 emission is quite uncertain, and the uncertainty increases over time. Projections of emissions in 2020 vary between 7.1 and 13.4 billion metric tons, while 2030 emission are expected to be between 6.1 and 14.9 billion metric tons. By 2050, the range is especially large: 3.5-16.7 billion metric tons. The comparative analysis also showed that China's CO_2 emissions from energy in the high-emission scenario would be on average 11.2 billion metric tons, peaking in 2040 at 13.8 billion metric tons; in the medium-emission scenario, the figures would be, on average, 9.6 billion metric tons, peaking in 2030 at 10.5 billion tons; and in the low-emission scenario, 8.9 billion metric tons on average in 2020, peaking in 2025 at 9.1 billion metric tons.

The gap between projections even within grouped scenarios is significant enough to conclude that China's CO_2 emissions perspectives are quite uncertain, depend on number of factors. And the gap becomes larger when more modeling results are considered. Figure 1 shows a range of emissions projections from 80+ models, collected from various studies and emissions projections databases. All scenarios are grouped by emissions peak time: before 2030, representing China's Paris commitment, and after 2030 (or no peak). As shown on the figure, he two groups of scenarios overlay in emissions levels.

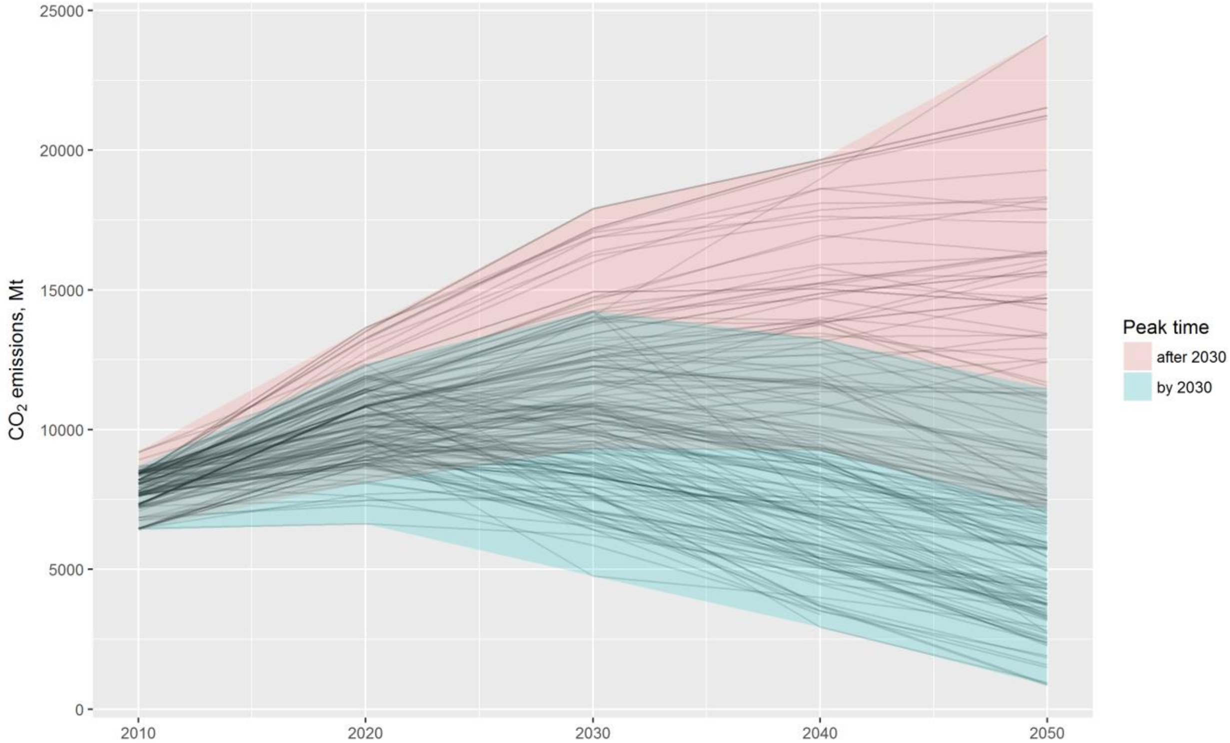

Figure 1. Combined emissions projections from international sources.

Source: AME (2012), AMPERE (2014), BP (2016), EIA (2016), IDDRI/SDSN (2014), IEA (2016), LIMITS (2012), Kriegler et al. (2013, 2015), Liu, Q. (2015), Reilly et al. (2015), Riahi et al. (2015), World Bank (2013), Zhou (2011).

Certainly, the scenarios have different underlying conditions, but, disregarding the input differences, the figure demonstrates the range of uncertainty resulting from various assumptions, and causing more challenges for direct consumers of the projections, the decision makers. A comparative analysis of modeling methods, data sources, key hypotheses and assumptions can potentially shed light on the differences in projections, improve models' and scenarios' understanding, and application. However, complete and systematic data on different model groups is not typically available with results, so it is difficult to adequately compare models, and build confidence in modeling results.

China Energy Modeling Forum (CEMF) is an initiative which establishes a model comparison and exchange platform, guided by the principles of openness, fairness, transparency and neutrality. The platform promotes communication and gives researchers opportunities to discuss the mechanics and conditions used by different models. This, in turn, allows the participants to investigate and explain the divergences in modeling results, and improve their models accordingly. In light of the ongoing discussion on the carbon emissions peaking and its importance for China's low-carbon transformation and sustainable development, in 2015 CEMF initiated the comparative study of China's carbon emissions peak level and timing. The main goal of the study was to investigate sources of uncertainty in carbon emission projections, whether coming from models' theory and structure, data, or scenario assumptions. Five modeling teams with seven different models participated in the study. CEMF conducted three semi-annual open meetings, several technical workshops and ad-hoc meetings. Experts from industries and economic sectors, businesses, public institutions, and academia were invited to discuss and compare data, assumptions, emissions and energy balance projections results. The main focus of the study was directed towards emissions peak time and level in the Chinese economy and main energy consuming sectors and industries. The CEMF01 study concluded in the end of 2016. This report describes a structure and the key findings of the study, and lays out demand for further research, energy models and emissions analyses improvements.

Methodology

The main idea of a multi-model study is based on beliefs that scientific inference should not depend on an arbitrary model selection or individual's subjective judgement. If modelers agree on assumptions, then results should be consistent across models, i.e. considered reliable. Differences in results should have a rational explanation either stemming from data, subjective views on economic perspectives, or from models themselves.

Since every model is just a set of mathematical equations which express relations between variables and parameters, the link between the model's output and input is rational by definition, and in theory can be traced. Though in practice, it is not easy to achieve. Due to growing complexity, demand for higher precision and details, this rational link can be hidden under number of variables and dependencies. And even if models share the same techniques and structure, every model is unique in the hands of a researcher who calibrates it, reviews data and parameters, designs policy experiments. All the steps require inputs from researchers and include some subjectivity. Harmonization of key inputs should presumably reduce divergence between models' outputs, i.e. provide more comparable and consistent result across models.

The harmonization of models' input has several goals. First, it reveals differences in modelers' views, and promotes discussion. Second, it helps to identify a level of uncertainty on each particular topic of disagreement. If it is hard to reach consensus on the level of a particular parameter or input, the potential range can be identified instead, expressing the boundaries of the uncertainty. A serious obstacle for harmonization is models' theory and structure. The high-level comparison could be considered in cases when models' input is hard to harmonize. Therefore the comparative differences in results will be likely assigned to both – the models' theory and parametrization, which will be also hard to decompose.

In this section, we describe the two key types of models applied to energy and emissions projection, characterize participating in the CEMF01 study models, and discuss the design of the comparative analysis, scenarios, and the CEMF01 process. We start with comparative details of the mainstream modeling techniques, general features and assumptions of their theoretical framework, and underlying assumptions of the models involved in the study.

Modeling approaches and CEMF01 study models

The broad variety of computational models applied to energy, economy and climate change-related analyses can be distinguished into two groups based on the way they approach the link between energy, emissions, and economic activity. The first group, so-called "Top-Down" (TD) models, describe economy as a system of linked by equations economic aggregates, reported by statistical agencies, and expressed in currency units. Output, value added, capital stock, employment, input-output table (IOT) and social accounting matrix (SAM) are the normal bricks of

TD models. Computable (or applied) general equilibrium models (CGE or AGE) are mainstream TD models.

The second group is so-called "Bottom Up" (BU) or technological models which focus on material and energy flows in physical quantities, starting from production through all stages of transformation to the final use. BU models are also called "reference energy system" (RES) models because they represent a snapshot of an energy balance (depending on a model scope, it can be national, regional, or industry-level) and perspectives on its development, based on available technological options. The mainstream BU models, such as TIMES/MARKAL[3], OSeMOSYS[4], MESSAGE[5] are systems of linear equations, with an objective to optimize development of an energy system over time based on least costs, and policy constraints, with assumptions of known, exogenous final demand in the long run.

Both types of models are actively involved in emissions simulation and assessment of climate and energy policies impact on economy, energy costs, and feasibility of emissions abatement. However, they are addressing the issues in different ways, designed to answer different questions. TD models are more focused on macro-level adjustments of economy to potential "exogenous shocks", such as changes in taxes, tariffs, introduction of a carbon price, or a constraint. While TD models cannot provide clear insights on how switching between energy types can be achieved from technology perspectives, BU models don't operate with key economic variables as GDP or employment. Their main focus is technological feasibility of a particular policy with associated direct costs and required investments.

An important step in comparison of different modeling approaches is and understanding what models' input and output are, and how the output depends on the input. For the emissions peaking analysis, the output of our interest is CO_2 pathway up to 2030 and beyond, or, more precisely, emissions level, and the year of the peak. Presumably, all factors affecting the emissions level and peak can be combined in four broadly defined factors:

- level of economic activity,
- energy efficiency,
- switching to lower carbon fuels,
- and direct emissions control.

Though the two modeling approaches have enough differences in underlying theoretical framework, table 1 summarizes the main characteristics, which are potentially important for comparative analysis of emissions projections.

Table 1. Technical differences between the TD and BU modeling approaches.

Characteristic	Mainstream Top-Down	Mainstream Bottom-Up
Model's "Top" level	Social accounting matrix (SAM)	Energy balance
Model's "Bottom" level	Economic agents (producers, consumers), maximizing their objective functions (profits, utility).	A set of technologies, describing current and alternative ways of production (transformation) of one commodity to another.
Main data and exogenous	SAM, key parameters of production, consumption, and trade functions,	A stock of technologies with potential alternatives, described as a set of

[3] http://iea-etsap.org/index.php/etsap-tools/model-generators/times

[4] http://www.osemosys.org/

[5] http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html

Characteristic	Mainstream Top-Down	Mainstream Bottom-Up
parameters (model input)	taxes and tariffs rates.	technical (efficiency) parameters and costs.
Endogenous variables (model output)	Aggregated welfare and GDP, output, capital, and employment by sectors.	Total discounted system costs; a set of technological chains to produce every final product.
Drivers of economic activity growth	Exogenous productivity growth, capital and labor supply.	Exogenous demand for every final commodity.
Productivity growth	TFP, capital, labor, materials, and energy productivity growth are exogenous parameters, assigned to every sector	Since there is no labor in the models, the productivity is relevant to capital and energy only. The technology-level productivity is exogenous, but aggregated productivity is endogenous.
Energy efficiency	Exogenous part (parameters of production functions) and endogenous (substitution between capital and energy, also interpreted as non-fossil energy use) parts	Energy intensity (productivity) of final products is a result of endogenous technological choice
Energy substitution	Based on elasticity parameters in production functions	Based on available alternative technologies and their costs
Dynamics	Recursive (static model with step-by-step updating)	Intertemporal optimization
Expectations	Myopic, policy or technological change is not included into optimization.	Perfect foresight, all future changes are included into optimization.
Policy	Expressed as a change in exogenous parameters or constraints on particular endogenous variable.	Expressed as a set of constraints on a group(s) of technologies, commodities, costs
Algebraic representation	A system of nonlinear (or linearized) equations	A system of linear equations
Solution method	Various rebalancing algorithms to fit a new set of exogenous parameters and constraints	Linear programming algorithms

Every of the four factors could directly depend on a model input parameters, or being a result of interaction of the model's endogenous variables. From comparative modeling study of emissions projections it is essential to distinguish to which extend the results are predetermined by the model input. Some high-level judgements can be done based on a model theory only, disregarding the model structure. Let's discuss every of the four factors in details.

Economic activity requires energy. Higher economic activity (ceteris paribus) requires yet more energy with direct consequences for carbon emissions. It is clear from the table above that growth of an economic activity in both types of models directly linked with exogenous drivers. In the case of TD models, the baseline economic growth is mostly defined by exogenous productivity growth assumptions, and capital and labor supply assumptions. In BU models, the production of final commodities is predetermined by exogenously assumed final demand. Based on a model structure, the final demand can be electricity, steel or any other products like passengers-kilometers, building area lighting, or use of electronics. Since the aggregated economic activity dynamics, or baseline, heavily depends on a set of exogenous parameters in both types of models, a substantial part of this factor of demand for energy is predetermined in the energy models. Certainly it should be noted that structure of economic activity has significant endogenous component, and restrictive policy can potentially reduce level of activity (income), especially in TD equilibrium models.

The second factor, **energy efficiency**, is partially exogenous and partially endogenous in both types of models. Energy efficiency in TD models can be defined as a particular parameter in production function or more broadly as an energy intensity of production, i.e. energy consumption per a unit of output. It depends on the form of production function, as well as economic structure (for economy-wide energy efficiency measures). The exogenous part in TD models is introduced as an energy efficiency improvement for a particular scenario, f.i. baseline. A policy-induced, endogenous change in energy intensity is normally modeled as a substitution between energy and capital. Higher capital costs are interpreted as investments in renewable, nuclear and/or energy efficient technologies.

In BU models, exogenous part of energy efficiency is embodied in technical parameters of alternative technologies, which could have higher efficiency parameters. The decision of switching to alternative technologies is endogenous and based on available options and their costs.

The third factor, **fuels switching**, works similarly with endogenous part of energy efficiency. In TD models, fuel switching is normally based on elasticity of substitution parameters in the production functions, which are exogenous, and also depends on competition for energy between industry and trade. The elasticity concept is a simplification from technological perspectives, which makes the production functions on TD models more flexible and applicable to energy modeling issues. The downside of simplification is a penalty for divergence from the baseline, especially when the changes are significant. BU models, on the contrary, are too swift for change. Linearity leads to a "winner takes all" problem, when a marginal difference in costs keeps alternative options behind. The properties of the two modeling approaches are well known; number of studies reported a pattern that TD models tend to overestimate costs of emissions abatement, whereas BU models are tend to underestimate inertia of technological transition.

The fourth potential source of emissions reductions is **direct emissions control**. There are not so many options for direct control of CO_2 emissions other than carbon capturing and sequestration (CCS). The technology has been considered as an option in several of participating in the study BU models. However, it was not in use in the presented below scenarios, and the factor will be dropped from further consideration.

The three remaining sources of emissions reductions are consistent with widely used Kaya decomposition. We don't consider population growth since it is more relevant for international comparisons:

These three sources of emissions reductions are consistent with widely used Kaya decomposition. We don't consider population growth since it is more relevant for international comparisons:

$$F = G * \frac{E}{G} * \frac{F}{E}$$

or in growth terms

$$g_F = g_G + g_{\frac{E}{G}} + g_{\frac{F}{E}}$$

where

$F -$ CO_2 emissions from fuel combustion,

$G -$ GDP (for Top-Down models) or level of output (or composite output index) for a particular sector,

$E -$ total energy consumption by a sector or total primary energy supply for TD models,

g_x – denotes logarithmic growth of x.

The later equation will be used for decomposition of CO_2 emissions growth g_F by sources: economic growth (g_G), growth of energy intensity of final product ($g_{\frac{E}{G}}$), and growth of carbon emissions intensity of used energy ($g_{\frac{F}{E}}$).

The CEMF01 study is based on comparative analysis of emissions projections from seven different models, listed in Table 2. The three first models (SICGE, CAS-PIC, and China-MAPLE) cover 100% of CO_2 emissions from fuels combustion in China. SICGE and CAS-PIC relate to Top-Down class, whereas China-MAPLE is technology-based multi-sector Bottom-Up model. The other four models are one-sector Bottom-Up technological models, which cover altogether around 70%—80% of emissions from fuel combustion (see table 3). Electric power sector, iron and steel, and cement industry are minimal costs optimization models. Transportation sector model is a simulation-based, where costs are not considered.

Table 2. A set of participating the study energy models.

Model name (abbreviation)	*Organization*	*Sectors and regions*	*The model theory*
SICGE (SGE)	SIC	National, multi-sector	Applied General Equilibrium (AGE), welfare maximizing
PIC-Macro (PIC)	CAS	National, multi-sector	Econometric general equilibrium (REMI-CGE)
MAPLE (MAP)	Tsinghua E3	National, multi-sector	TIMES – partial equilibrium cost-minimizing
NCSC-ELC (ELC)	NCSC	Electric power sector	TIMES – partial equilibrium cost-minimizing
SIC_IIS (IIS)	SIC	Iron and Steel sector	"Bottom-Up" partial equilibrium cost minimizing
PRCEE_CEMENT (CEM)	MEP/PRCEE	Cement industry	TIMES – partial equilibrium cost minimizing
LEAP_TRA (TRA)	MEP/PRCEE	National, one sector	LEAP simulation
COMBI (COM)	Combined results from four one-sector models: NCSC-ELC, SIC_IIS, PRCEE_CEMENT, LEAP_TRA		

The simulation results from one-sector models could be merged and compared with national-level projections with the following caveats in mind: the estimates for each sector have been made by different teams, and, more essentially, projections for every industry have been made without any harmonization with others. The combined estimates from one-sector models are presented in the comparative figures as "COMBI" model (see Table 2). Not covered part of emission by these four models is estimated as a difference between 9Gt CO_2 (an approximate level in 2015) and sum of sectors emissions in 2015. The dynamics of the remaining part is assumed to follow the same growth rate as the combined sectoral emissions.

Table 3 describes emissions structure by sectors, covered by BU models in the study. The two Top-Down models distinguish much more sectors and cover 100% of emissions. The definition of sectors in Bottom-Up and Top-Down models differs significantly, which makes it more difficult for comparative analysis. The last column in the table lists models used for sector-level comparative analysis.

Table 3. Main economic and industry sectors, considered by the study.

Name of the sector	*Share of CO_2 emissions in 2014 (IEA estimates)*	*Bottom-Up Models*
Electricity and heat	48%	NCSC-ELC, MAPLE
Iron and steel	14%	SIC-IIS, MAPLE
Cement	~7(+7)%*	PRCEE_CEMENT, MAPLE
Transportation	8%	PRCEE_TRA, MAPLE
Residential and buildings	~5%**	MAPLE
Others	~15-20%	MAPLE

* - estimate, number in parenthesis includes emissions from processes

** - excluding heating

This set of participating CEMF01 study models represents a sample of energy models of diverse structure and theory, widely applied for emissions simulation, energy, and climate policy analysis, and thus provides a good platform for comparative analysis on national, sector, and cross-theory levels.

Scenarios structure

The goal of scenarios definition in the study is twofold. First, scenarios should cover the potential range of uncertainty, researchers meet while simulate economic development and emissions pathways. Second, the number of scenarios should be minimal in order to make side-by-side comparisons between models and scenarios feasible. From another perspective, more can be learned from the comparison about models' differences, if input to the models, scenarios, are harmonized. However, harmonization of assumptions and data between models is not always straightforward, especially between models of different frameworks, such as BU and TD. In the study we aimed for harmonization within groups of models of the same theory. This is done for key parameters of CGE models. Key input parameters for the BU models are studied to examine the differences in results.

There are three levels of scenarios in the study: initial, actual, and final. The first,"initial", set that could be also named "full" set is shaping the scope of the study. Table 5 describes the scenarios matrix with 3 different times of peaking (before 2025, before 2030, and after 2030), and two subjective measures of level of economic activity (low and high). From international liability perspectives, scenarios in the two first rows satisfy the peaking commitment. From the national perspectives, higher economic growth is always preferable (ceteris paribus), therefore scenarios in "High" column can be considered as preferable from economic growth perspectives. One can say that the absolute winner in the scenarios set is the scenario with earliest peaking and high growth, because it is favorable from international perspectives and climate change mitigation, and high economic growth is observed.

During the CEMF01 process, participating in the study modeling teams were asked to provide two scenarios with the commitment peak year (2030), early peak (before 2025) if possible, and voluntary late peak (after 2030) in case the solution of early peaking is considered unrealistic by the teams, or unfeasible from their modeling results. Harmonization has been made only for GDP growth and population growth, which are drivers for TD models. Figure 2 displays a range of

GDP projections for China, acquired from several studies, and CEMF scenario, which represents optimistic growth scenario consistent with the “New normal”.

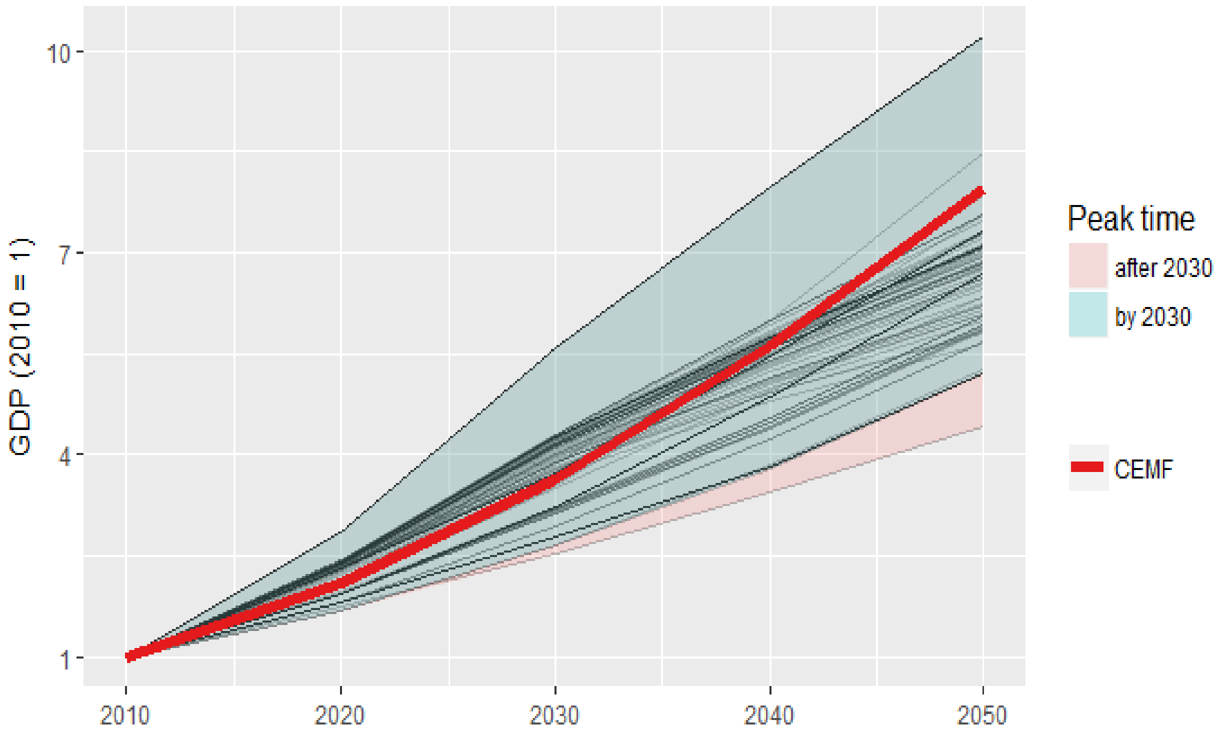

Figure 2. GDP projections assumption in CEMF and other models.

Source: AME (2012), AMPERE (2014), BP (2016), EIA (2016), IDDRI/SDSN (2014), IEA (2016), LIMITS (2012), Kriegler et al. (2013, 2015), Liu, Q. (2015), Reilly et al. (2015), Riahi et al. (2015), World Bank (2013), Zhou (2011).

The level of drivers for Bottom-Up models has been left to the discretion of modelers, based on their vision of particular sector development, and feasibility of the emissions peak scenario. Instead of harmonization of the Bottom-Up drivers, we compare them in order to identify the sources of uncertainties, differences in projections, and to extend the floor for discussion between modeling teams and industry experts.

Table 5 describes the structure of scenarios. The main classification of scenarios has been assigned based on the level of emissions – “High”, “Low”, and “Base”, which is subjective classification of scenarios for each model. “Base” scenario is non-peaking, provided by MAPLE modeling team for comparative reasons. Cement, Iron and Steel industry models demonstrate declining drivers, and were provided with only one scenario.

Based on the submitted projections, some sectoral models had two versions of drivers, which were contingently named as “Moderate” growth, and “Soaring” or relatively higher growth. For example, electric power sector in NCSC_ELC model had two levels of drivers; multisector MAPLE models had two scenarios with two different levels of drivers for some sectors, and only one for others. Combined estimated (COMBI) were merged based on levels of emissions and drivers.

Table 4. Scenarios matrix based on emissions peaking time and drivers level.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Level of drivers</td></tr>
<tr><td>Moderate</td><td>Soaring</td></tr>
<tr><td rowspan="6">Time of the peak</td><td rowspan="2">Before 2025
(early peaking)</td><td>NCSC_ELC.low, COMBI.low</td><td></td></tr>
<tr><td colspan="2">SICGE.low, PIC_Macro.low,
PRCEE_CEMENT, SIC_IIS</td></tr>
<tr><td rowspan="2">Before 2030
(commitment)</td><td></td><td>COMBI.high</td></tr>
<tr><td colspan="2">SICGE.high, PIC_Macro.high,
MAPLE.high, LEAP_TRA.low</td></tr>
<tr><td rowspan="2">After 2030*</td><td></td><td>NCSC_ELC.High</td></tr>
<tr><td colspan="2">MAPLE.base, LEAP_TRA.High</td></tr>
</table>

* - “After 2030” peak is a voluntary scenario which is reserved for cases when “commitment” peaking difficult to simulate from a particular model perspectives. It is helpful to have such option from modeling perspective, especially for particular sectors, though the participating teams were not required to simulate it, the scenario was optional.

The CEMF01 process and timeline

The methodology of the comparative study, as described above, has been integrated into CEMF01 working process. The study announcement (May 2015) followed with CEMF conference (Nov 2015), where various modeling teams presented their studies on economy-wide and sector-level CO_2 emissions projections, disclosed and discussed details on their modeling methodologies, and expressed their interest in participation in the CEMF01 study. CEMF conferences have two days format, and include policy and technical discussion. As a result of the conference, the CEMF01 core modeling group has been formed to carry out the study.

During 2016, three technical workshops have been conducted where the scenarios have been formulated, assumptions discussed, with following rerun and reconsideration of modeled scenarios as required. Technical workshops are essential stages of CEMF process, where modelers discuss their results and are getting feedback from leading industry experts, stakeholders, and academia, learn industry and policy insights, share and discuss ideas.

The comparative results have been presented and widely discussed on the CEMF annual meetings in Dec 2016, when the study was officially concluded, and CEMF02 study of Low emissions development strategy for China was launched. Final results of the study have been discussed by the CEMF academic committee in June 2017 with following publication of the report.

Multi-model comparative results

The comparison of national level emissions pathways by scenarios and models is presented on Figure 1. Some divergence in emissions estimate for 2015 is due to several reasons, related to the base year calibration and the data. Base year is the starting point of each simulation model, calibrated to a particular data. Rapid economic growth in the last decades, energy consumption, and emissions are changing very fast. Models calibrated to earlier years need to be updated accordingly to be able to represent the current level of economic variables. Limitations in the software also might be an obstacle to make the interim dynamics of the models following the real data difficult. Recursive dynamics and static models, and their software are not normally designed to make the models following the real data. The goal of calibration of Top-Down models is normally limited to representation of the main economic variables in the latest state of the economy, where the data is available. The updating process of CGE models is quite difficult and requires additional study, which involves updating of social accounting matrix (SAM) consistent with physical energy consumption structure by sectors.

The models participating in the study have different base years. For example, PIC_macro model is based on 2007 input-output data, MAPLE is calibrated to 2010, SICGE – to 2015, the sector-level models were updated to 2013-2014. Variation in base year calibration, as we observe in Figure 3, result in divergence in levels. The bigger gap between base years leads to higher divergence in 2015 data, which is also a simulation result in most models. However, the error is not so notable when dynamics between models is compared. Below we compare both, the levels and dynamics of emissions, indexing trends to the first year.

Disregarding emissions differences in the first considered year, emissions level in “high” emissions scenario is close to 10 Gt in 2030 for the models. Emissions peak is reached by 2030 (around 2025 in SICGE model). Maximum emissions level in “Low” scenario is around 9Gt for all models, with peak around 2020-2025.

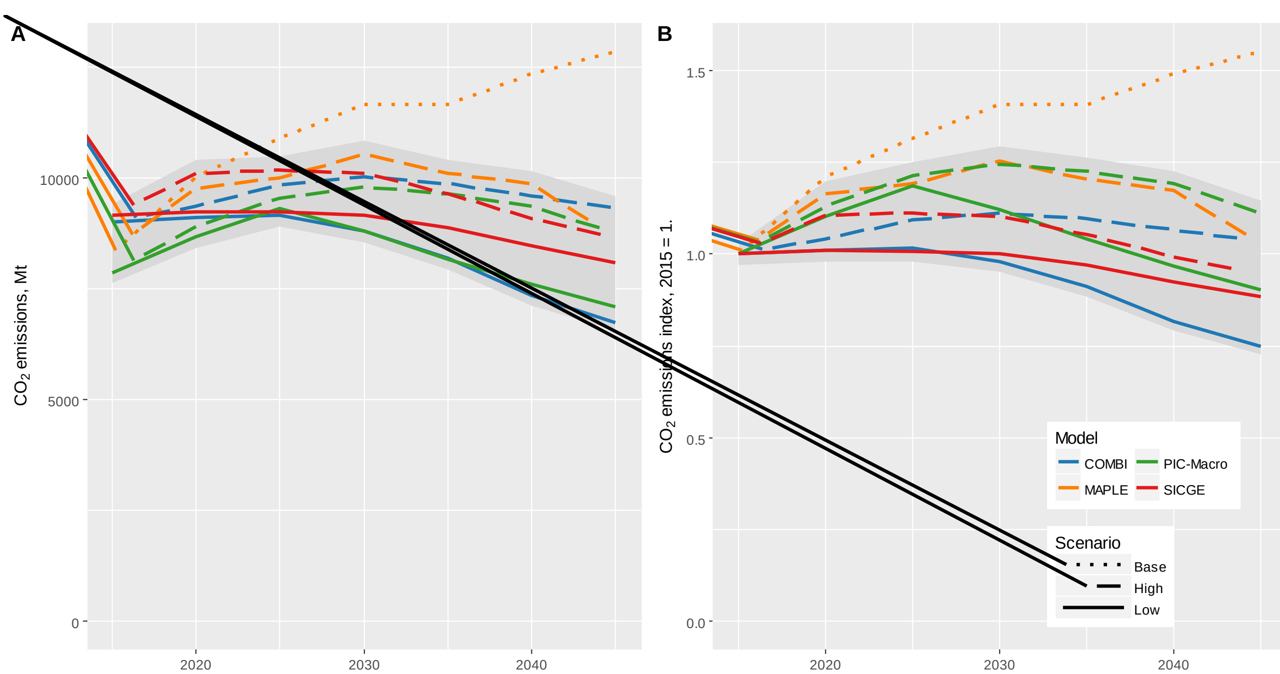

Figure 3. CO_2 emissions projections by models and scenarios.

The main difference between "High" and "Low" emissions level in 2030 is determined, dynamics from 2015 to 2020 and 2025. Higher emissions scenario in PIC_Macro, MAPLE, and SICGE show high growth of emissions by 2020. However, based on the data available in the beginning of 2017, CO_2 emissions in 2016 are about equal to 2015 or even lower . If the trend continues, the emissions level is not likely to grow by 2020 significantly, as described by the scenario, and the emissions level is not likely to reach the upper bound of the scenarios. The "High" emissions scenario in combined sectoral estimates (COMBI), as well as "Low" emissions scenario by PIC_Macro, assume lower emissions growth by 2020, and more notable growth after 2020. "Low" emissions scenarios by SICGE and COMBI demonstrate almost flat emissions pathway up to 2025 followed by reduction.

Emissions trends indexes for all peaking scenarios are presented in Figure 3 (right). Assuming the total emissions in 2015 is equal 9 Gt, the range of projected emissions in peaking scenarios will be 9.1—10.5 in 2020, and 8.9—11.25 Gt in 2030. The adjustment to the starting year (2015) differences in projections doesn't result in notable changes in emissions range in 2030. There are also not many notable differences between models of different theory (TD and BU) on the aggregated level. The upper emissions bound is edged by two models – PIC_Macro (TD) and MAPLE (BU). The lower bound from 2015 to 2030 is outlined by SICGE (TD) and COMBI (BU), with almost coinciding projections in both upper and lower bounds. The variation of the emissions level in the peak is about 2Gt, or around 20%, which is significant uncertainty. However, it is notably lower when compared with larger sample of models and scenarios (see figure 4).

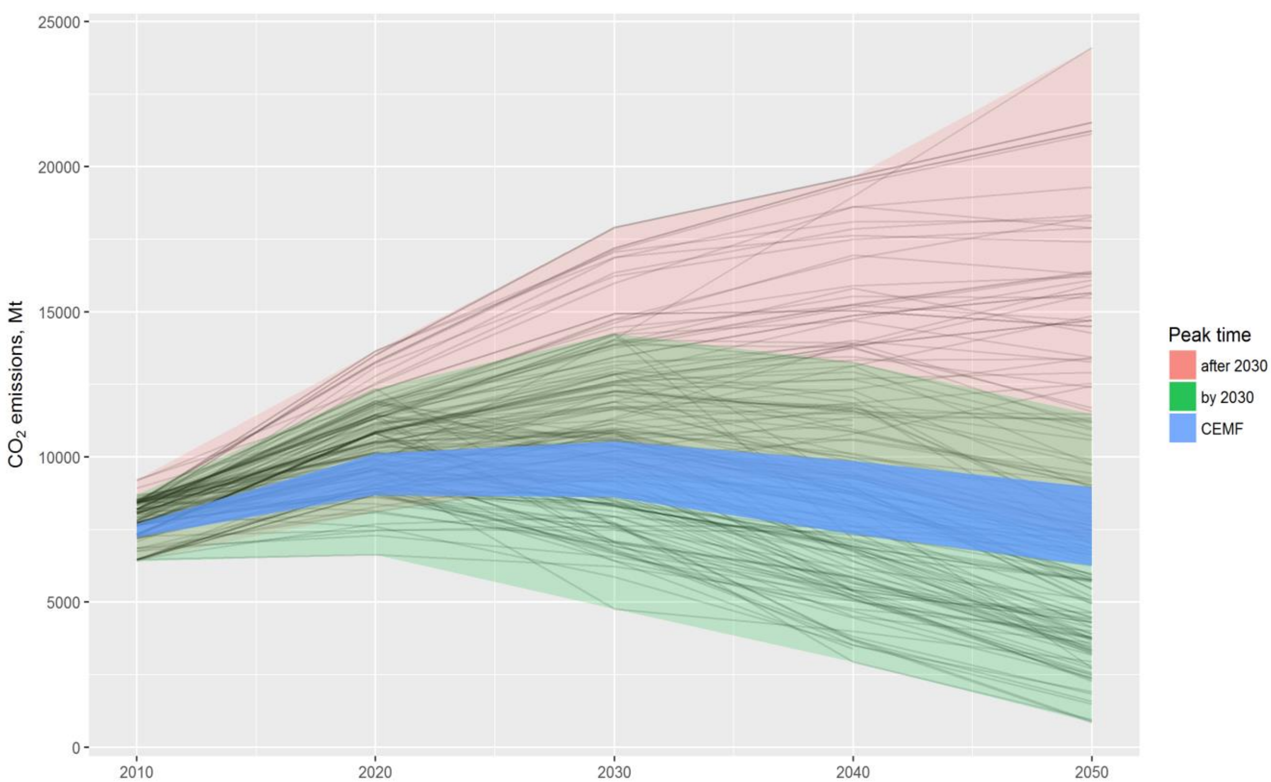

Figure 4. CEMF peaking scenarios vs. other emissions projections.

Source: same as sources for Figure 1 plus CEMF01 estimates.

It is clear that emissions peaking scenarios require phase out of fossil energy use, especially coal. All models show coal peak by 2025. In High emissions peaking scenario coal peaks by 2020 in MAPLE, SICGE, and COMBI models. In Low emissions scenarios coal peak around 2015 in SICGE and COMBI models, and around 2020 in PIC-Macro (see figure 5). Consumption of oil and natural gas is growing in all scenarios. Growth of oil in MAPLE model peaking scenario is substituted with natural gas. Other models demonstrate moderate development of gas use.

The dynamic of aggregated non-fossil energy sources is similar in all models for peaking scenarios. PIC-Macro doesn’t distinguish different sources of non-fossil energy. Other models show quite different structure of non-fossil energy, especially nuclear and renewables. The variation shows, on one hand, uncertainty in the non-fossil energy development, and various available options; on the other hand, which is hard to prioritize from current modeling perspectives. More studies are required here to address the uncertainties and develop optimal and robust technological pathways for particular industries and energy sources.

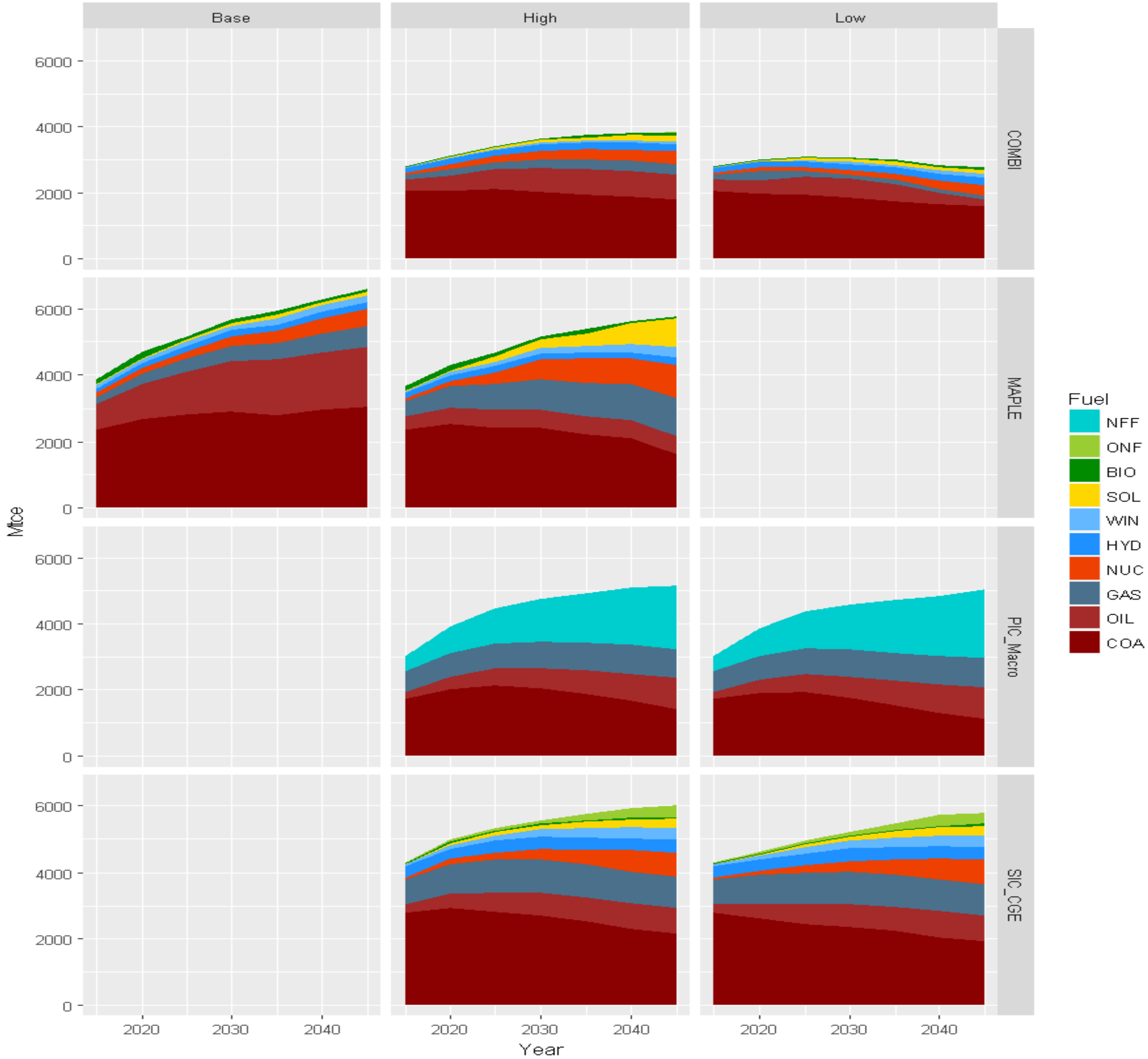

Figure 5. Total primary energy supply (TPS) by fuel types, models, and scenarios.

Aggregated energy sources into two category:
* FFL - fossil fuels * NFF - non-fossil fuels

The structure of emissions by sectors from Bottom-up models is presented in Figure 6. Unlike the national emissions level and energy balance structure, sector-level projections are very different in TD and BU models. Here, we consider only BU projections for sectors, which are more consistent with experts' opinions on particular industries development. The efforts towards harmonization of results between TD and BU should be considered in the future to make the results more comparable across models' theory.

The main source of carbon emissions is electric power sector, which will play important role in future emissions trends. Emissions from transportation are also growing by 2030, as well as "Other," or unmolded, emissions in MAPLE model scenarios (the share of "Other" emissions is assumed constant in COMBI). Emissions from Iron and Steel, and Cement production are declining in all scenarios.

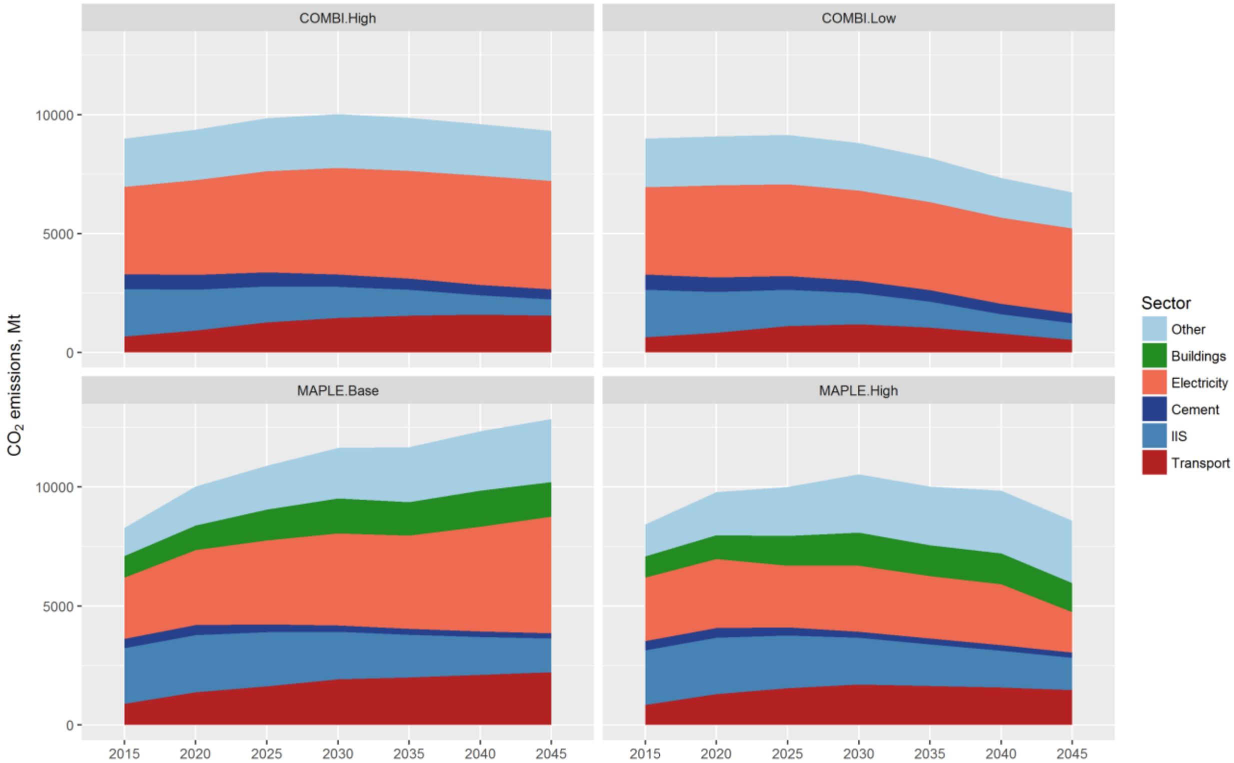

Figure 6. CO_2 emissions structure by sectors.

Figure 7 shows CO_2 emissions trends and Kaya decomposition of emissions changes by sources from 2015 to 2030 by BU models and scenarios. MAPLE scenarios assume low variations in electricity demand between the two scenarios. As follows from the Kaya decomposition for the sector, the main factor of almost 50% emissions growth in the industry is demand. Energy efficiency and carbon intensity of the used fuel inputs mix are improving slowly. On the contrary, MAPLE peaking scenario has more significant change in fuel mix towards non-fossil energy (see Figure 5), which results in almost zero carbon emissions growth by 2030 even with higher demand vs. "Base" scenario. NCSC_ELC model scenarios assume comparable growth of electric demand in "High" emissions scenarios, but twice lower in "Low" emissions case. From other perspectives, NCSC_ELC scenarios demonstrate higher energy efficiency improvements in the sector by 2030 vs. MAPLE scenarios. The fuel mix changes towards non-fossil energy with lower temp than the demand. Therefore, the main source of emissions reduction in "NCSC.Low" scenario is demand reduction, indicating requirements for demand-side energy efficiency improvements, i.e. electricity consumers.

The main source of emissions in transportation sector is growth in demand. MAPLE scenarios on average assume more than doubling of demand for transportation services. Drivers in LEAP_TRA scenarios are more moderate and close to GDP growth assumption. The structure of demand for transportation services also differs in the two models. In LEAP_TRA scenarios, freight transportation is growing faster, reducing aggregated energy efficiency in the sector. The carbon intensity of the fuels does not change by 2030. Both MAPLE scenarios are observing some energy efficiency improvements in the sector. Some variation in sources of emissions changes between the scenarios and models is mainly due to changes in the sector output structure and base-years.

Notably, both models don't consider higher penetration of low-carbon vehicles before 2030. Recent boom in electric and hybrid cars will be considered in further steps of research.

The cement and iron and steel industries have very different from electric power and transport sectors dynamic. Both sectors expect slowdown in demands due to transportation of the China's economy. Scenarios in both models agree with the negative dynamic after 2020, though the speed of reduction, and the year of peak differs. MAPLE scenarios expect peak in the demand in both sectors in 2020. SIC_IIS and PRCEE_CEMENT models' scenarios assume that peaking in IIS and cement industries are around 2015. Emissions reduction in IIS industry mainly changes in demand. SIC_IIS scenarios also assume expansion of heat recovery technologies, which change overall fuel mix structure and efficiency (installation of heat recovery technologies improves average energy efficiency in the industry, and reduces net demand for electricity produced outside the sector – see Kaya decomposition for the sector). The sources of emissions reduction in cement sector are alike in both models, and include demand reduction of demand, energy efficiency improvements, and some growth of carbon intensity of the aggregated fuel mix, which is also a function of expansion of heat recovery technologies in the industry.

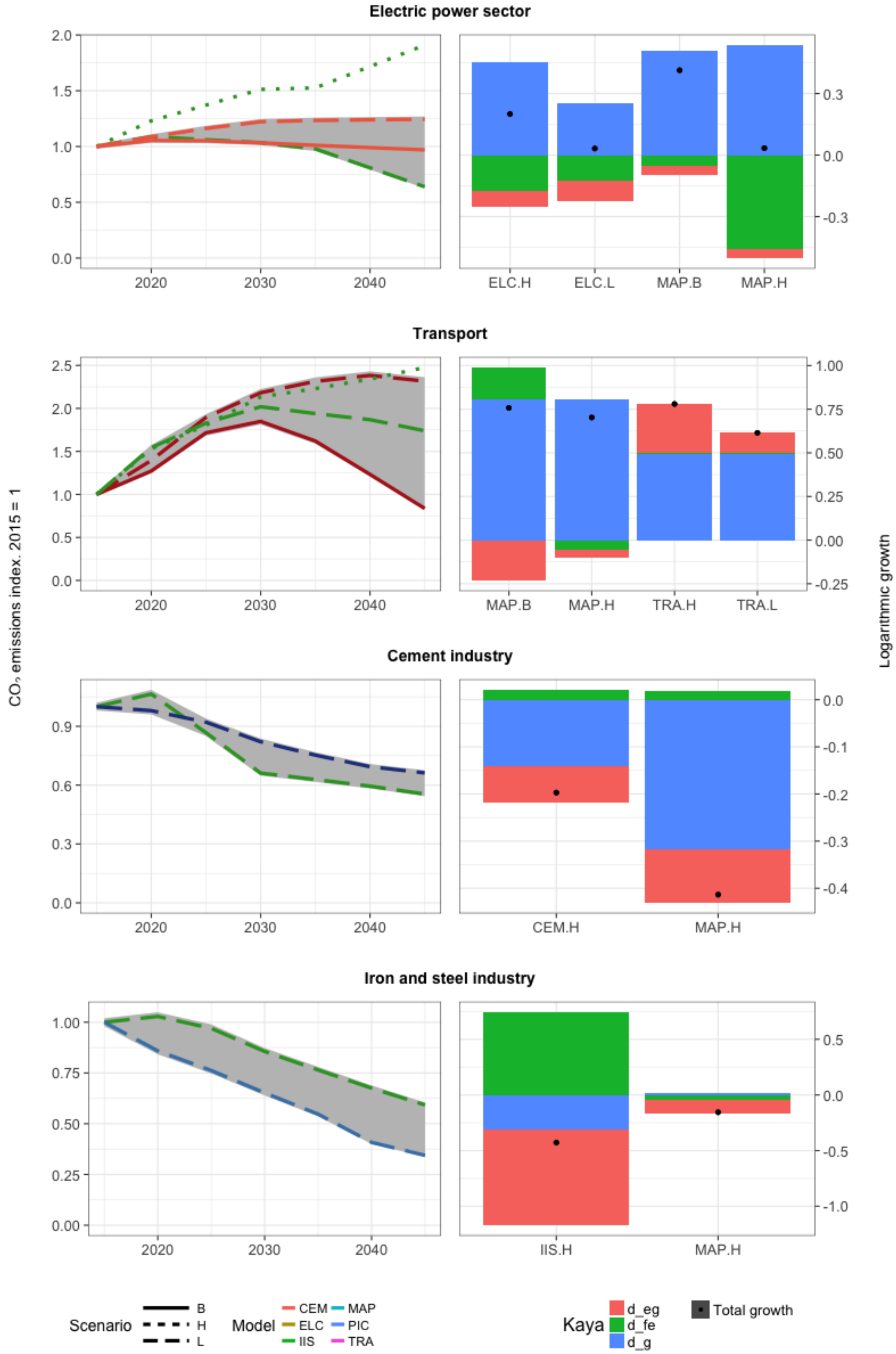

Figure 7. Carbon emissions dynamics by sectors.

Conclusions

The aim of CEMF01 study is to address differences in carbon emissions projections across energy models; to identify the peaking conditions and underlying assumption in the emissions peak and level projections; to research sources of the projections divergence, either going from data, models' theory, or scenarios' assumptions; and reveal uncertainties in the projections, which potentially affect carbon emissions level and the peak. The study combines and compares projections from seven different models with various scopes of emissions coverage and theoretical frameworks. During the study process, the projections and underlying factors have been openly discussed between modeling teams, industry experts, and academia. The results of the study can be summarized into two groups: findings about emissions level and peak, and about modeling practices with suggestions of a roadmap for further improvements of energy models and their application.

The emissions projections in the study are conditional to the required commitment to peak by 2030 or earlier, and should not be considered as given or most likely "business as usual" scenario. Though the study did not intend to evaluate certain policy measures, the policy is assumed to be efficient enough to reach the peaking and intensity goals. Considering the policy constraints, the economic and energy trends were simulated for the national and sector/industry levels to identify potential sources of emissions abatement, and the key sectors responsible for emissions peak and level.

According the modeling results, the CO_2 emissions level from energy use could peak from 9Gt (about the current level) to 11 Gt. The timing of the peak depends on the two main factors: the level of economic activity (economic growth, output of energy-intensive industries), and the speed of deployment of energy efficient technologies and non-fossil energy. The level of emissions peak will be determined mostly by the dynamics by 2020. Taking into account stabilization of emissions in recent years, which is not reflected in the considered scenarios, the earlier peak with lower emissions level could be considered as a more likely scenario.

Two energy intensive industries – iron and steel and cement – are expected to meet demand slowdown in the next decade. The CO_2 emissions in the sectors will likely peak by 2020 or have already peaked. Further improvements in energy efficiency in the industries could contribute to deeper emissions reduction. However, due to demand reduction, the new investments will be relatively harder to accomplish, and the strategies considered in the study are based on cost-efficient pathways.

The main uncertainties in the emissions pathways come from electric power sector and transportation. As expected, both sectors will observe significant demand increase in coming decades, but also have various options for emissions abatement. The emissions pathways in the sectors will depend not as much on demand growth, but on technological roadmaps – switching to non-fossil and low-carbon energy sources, as well as energy efficiency improvements.

Share of renewables (mostly wind, solar, bio) and other non-fossil energy sources (nuclear, large hydro) is already planned to grow by 13FYP. Further development will depend on both technologies competitiveness (costs of renewables, grid development, implementation of demand side management programs) and policy (introduction of ETS, 14FYP targets). Leveled costs of renewable and fossil-fuels fired technologies are comparable, but existing barriers don't allow to make projections for renewables based on least-cost models. Limitations of integration renewables to the grid and potential share of penetration was not considered by the study and needs special research with balancing models, which were not included in the study.

Transportation sector has a number of alternative technological roadmaps, which are also hard to evaluate based on the involved in the study models. The main mitigation technology in transportation is electrification and switching to biofuels and gas. Electric cars are penetrating the market very rapidly, though aggressive electrification has not been considered by the study due to uncertainties in costs of batteries, and required investments in infrastructure development, as well as policy support. Therefore, the scenarios for transportation could be considered as conservative development. Potential booming of transport electrification will speed up emission peak and lower the level.

The study also doesn't cover "other sectors" (around 20% of total CO_2 emissions from fuels combustion), which is hard to model and evaluate their technological roadmaps. Though construction and some other energy intensive industries could be considered on the next steps of the research.

Electric power and transportation sectors (as well as others) are key in carbon emissions reduction; more research should be done to identify cost-efficient emissions abatement strategies and policy measures. The ongoing implementation of emissions trading system will be a motivator for abatements in electric power industry. Complementary policies in transportation, such as energy efficiency and electrification, will insure achievements of carbon peaking commitment.

Several observations have been made regarding models development, application, and modeling approach.

Base year calibration, though it is less important for comparison of scenarios simulated with the same model, is a significant factor for differences in results in multi-model studies. Though keeping the models up-to-date is time consuming, the factor needs to be minimized on the further steps of research.

The data required for model development is not always available. Various estimates and approximations are normal modeling tools in this case. The data uncertainty and differences in assumptions is another important source of differences in projections, even for models of the same theory. Also, models themselves are not always absolutely transparent,even for researchers, and depend on the model or software developers. CEMF is going to develop data and basic models sharing platform to minimize the uncertainty and improve transparency and validation of data, models, and estimates.

The two different types of models have been applied, so-called Top-Down and Bottom-Up, and show similar results on national level for both energy balance and emissions levels. However, the two types of models show very different structure on sector and industry levels, and in general are not comparable. More research is required here towards harmonization of the two modeling approaches, because both types have different advantages and disadvantages in application to particular issues. Hybrid and integrated assessment modeling should be considered as a preferable direction in order to improve emissions projections and policy analysis.

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中国能源模型论坛（CEMF）由清华大学公共管理学院、清华大学产业发展与环境治理研究中心（CIDEG）与美国环保协会（EDF）共同发起成立，旨在为国内外能源、经济、环境和人类健康模型团队提供对话互动和观点交流的平台，为决策者和其他群体理解各类模型创造机会，共同推动中国能源与环境模型的能力建设，提升中国能源、环境与经济领域的科学决策水平。

The China Energy Modeling Forum (CEMF), initiated jointly by the School of Public Policy and Management at Tsinghua University, the Center for Industrial Development and Environmental Governance (CIDEG) at Tsinghua University and Environmental Defense Fund (EDF), is a platform for domestic and international modeling professionals working in energy, economic development, environment, human health and climate change fields to exchange and refine modeling ideas—and for non-technical policymakers and investors to improve their understanding of the strengths and weaknesses of different models in different applications. It aims to enhance capacity building of Chinese modeling teams, increase credibility of models and strengthen scientific policy development and decision making in the fields of environment, energy and economy with the support of modeling.

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FORUM

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