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The role of technology diffusion in a decarbonizing world to limit global warming to well below 2 °C: An assessment with application of Global TIMES model

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HIGHLIGHTS

- Three different technology learning approaches are introduced in the Global TIMES model.
- Technology diffusion can effectively reduce global mitigation costs and welfare losses.
- Developed countries should take the lead in low-carbon technologies' deployment.
- Technology cooperation will improve mitigation capability of developing countries.

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ABSTRACT

Low-carbon power generation technologies such as wind, solar and carbon capture and storage are expected to play major roles in a decarbonized world. However, currently high cost may weaken the competitiveness of these technologies. One important cost reduction mechanism is the "learning by doing", through which cumulative deployment results in technology costs decline. In this paper, a 14-region global energy system model (Global TIMES model) is applied to assess the impacts of technology diffusion on power generation portfolio and CO_2 emission paths out to the year 2050. This analysis introduces three different technology learning approaches, namely standard endogenous learning, multiregional learning and multi-cluster learning. Four types of low-carbon power generation technologies (wind, solar, coal-fired and gas-fired CCS) undergo endogenous technology learning. The modelling results show that: (1) technology diffusion can effectively reduce the long-term abatement costs and the welfare losses caused by carbon emission mitigation; (2) from the perspective of global optimization, developed countries should take the lead in low-carbon technologies' deployment; and (3) the establishment of an effective mechanism for technology diffusion across boundaries can enhance the capability and willingness of developing countries to cut down their CO_2 emission.

1. Introduction

In order to limit global warming to 2 °C or even 1.5°, both energy supply side and demand side need to be changed. The core of such transformation lies in the large-scale use of low-carbon technology on the supply side and the improvement of energy efficiency and fuel- and technology- switching on the end-use side. The advancement in low-carbon technologies can improve energy efficiency, reduce the cost of energy-saving technologies and non-fossil energy technologies, reduce dependency on fossil fuels, and avoid the rapid growth of CO_2 and other greenhouse gases. The IPCC 5th Assessment Report also highlights the importance of technological advances for stabilizing greenhouse gas concentrations [1]. In the current world of economic globalization, the exchange of capital, products and materials across boundaries has created a ground for international technology progress and diffusion [2]. The global spill-over of knowledge and technology allow a country to take advantage of international resources to build its own technological reserves and develop low-carbon technologies effectively and rapidly. The *Paris Agreement* stressed the importance of technical cooperation in achieving emission reductions, "*the urgent need to enhance the provision of finance, technology and capacity-building support by developed country Parties, in a predictable manner, to enable enhanced pre-*

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2020 action by developing country Parties" [3].

In energy system models, technological change is currently modelled either endogenously or exogenously [4]. The way in which the technological changes (cost and efficiency) are modelled in energy system models, often influence the model results, i.e., energy system development pathways and resulting energy system costs. Therefore, more and more models are beginning to consider endogenous technology learning (ETL), to investigate the impact of technology progress on energy systems [6–14]. Mattsson and Wene [6] modelled technology learning endogenously to solar photovoltaic (PV) and fuel cell in the GENIE model to assess the technology lock-in effect. The main conclusion is that early research investment is nee ded to reduce production costs. Seebregts et al. [7] attempt to introduce ETL in Western European MARKAL model. Their study focuses on technology learning and spillover effects of new technologies, such as wind and fuel cell. Model results show that technology learning and spillover significantly reduce policy costs. Gritsevskyi and Nakicenovic [8] explored ETL in MESSAGE model with consideration of scale effects and clusters effects of linked technologies. Their study also focused on technology uncertainty and long-term cost and benefit. Iyer et al. [12] applied technology learning and spillover endogenously in wind power and solar PV in GCAM model to explore the global and regional technology development strategies to achieve a long-term climate mitigation target. Their model results show that international cooperation in the deployment of low-carbon technologies can lead to substantial gains when achieving the global goal.

Technology learning is usually applied to a set of technologies which are competing or potentially complementary. Sano et al. [9] modelled ETL of fuel cell, wind and PV power in DNE21+ model. Rao et al. [10] included wind, PV and hydrogen production technologies in a hybrid model MESSAGE-MACRO. Barreto and Kypreos [11] have estimated learning by doing for PV, fuel cells and wind turbine. Iyer et al. [12] assessed wind and solar PV only. In this study, learning is applied to a set of low-carbon power generation technologies - wind, solar and CCS, which are important technology options in future low-carbon technology portfolios.

Most studies apply ETL to technologies individually. Several studies have examined the "cluster learning" phenomenon, which a cluster of technologies shares a common component that linked and learn together [7,13,14]. De Feber et al. [14] modelled ETL in fuel cell which leads to cost decline in transportation technologies. Seebregts et al. [7] applied learning to five clusters: wind turbines, solar PV, fuel cells, gasifiers and gas turbines. Anandarajah et al. [13] modelled multi-cluster learning in key vehicle components, namely automotive batteries, fuel cells, and electric drivetrains, which are shared across different transportation modes (buses, HGVs, cars). In Global TIMES model, several CCS generation technologies can obviously comprise multiple clusters. We incorporate a multi-cluster learning approach, applying learning for four types of coal- and gas-fired generation technologies, namely post-combustion coal CCS, oxyfuel combustion coal CCS, integrated gasification combined cycle with CCS (IGCC CCS) and natural gas combined cycle with CCS (NGCC CCS).

In this paper, technology learning is endogenously modelled in three different approaches into a 14-region energy system model Global TIMES to analyze the impact of technology progress and technology diffusion under the Shared Socio-economic Pathways (SSPs) [15–18], which provides a systematic scenario framework differentiated by socio-economic challenges to climate change mitigation and adaptation. It seems to be unique to model different endogenous technology learning mechanism under SSPs framework. The rest of the paper is organized as follows: Section 2 is a methodological section that describes the framework of Global TIMES model integrated with endogenous technology learning module; Section 3 provides the basic assumptions and scenario definition; Section 4 presents and discusses the model results and the conclusions are provided in Section 5.

2. Methodology

2.1. Overview of Global TIMES model

The TIMES (The Integrated MARKAL and EFOM System) is a combination of the MARKAL (Market Allocation Model) and EFOM (Energy Flow Optimization Model) developed and maintained by the ETSAP (Energy Technological System Analysis Program) of IEA (International Energy Agency) [19]. The Global TIMES, which is developed based on China MARKAL [5,20,21] and China TIMES [22–30] by Tsinghua University, is a 14-region global energy system model built on TIMES framework with a modeling period of 40 years from 2010 to 2050 with 5-year reporting period. It is a powerful and reliable technology rich bottom-up tool to study energy system development and carbon mitigation assessment for each of the regions. Global TIMES incorporates the whole energy system, including energy supply, energy conversion, transmission and end-use demand sector. Five demand sectors, namely agriculture, industry, commercial, residential and transportation, are modelled and further disaggregated into 26 sub-sectors in the Global TIMES. The model determines the least-cost mix of technologies and fuels to meet the projected energy service demands for a given social economic development scenario. The model is calibrated based on 2010 historical data from a series of statistics and reports and the main modeling results for the year 2015 are also calibrated to available publications [31–35]. In this study, the Global TIMES model has been further improved by integrating an endogenous technology learning module to apply technology learning endogenously for low carbon electricity generation technologies. Fig. 1 shows the region map of Global TIMES.

This paper focuses on the power sector which is becoming more and more important to low carbon society. In the model, we modelled more than 60 power generation technologies including existing and advanced low carbon technologies such as nuclear, hydro, onshore wind, offshore wind, solar photovoltaic (PV), concentrating solar power (CSP), biomass, CCS and etc.

2.2. Endogenous technology learning framework in global TIMES

Technology learning reflects the fact that with the accumulation of certain factors (e.g. knowledge, experience, utilization, etc.), technology may see cost decline. Several patterns of technology learning are observed by researches: learning by doing, learning by researching, learning by using, etc. [36]. However, it is difficult to consider all these learning patterns in the Global TIMES model. Nevertheless, in order to assess the cost reduction of low-carbon technologies, we modelled the learning by doing mechanism by introducing a one-factor learning curve into Global TIMES. Learning by doing is a concept which allows the evaluation of reduction in capital cost when a technology's cumulative capacity increases. In Global TIMES, only the investment cost undergoes learning. The learning curve is expressed by an exponential regression:

$$C_t = C_0 \times \left(\frac{Q_t}{Q_0}\right)^{\alpha} \quad (1)$$

where C_0 and Q_0 are the initial investment cost and initial capacity, C_t and Q_t are investment cost and cumulative installed capacity at time t, α is the elasticity of learning by doing. From Eq. (1) we can determine the progress ratio (PR) and learning rate (LR):

$$PR = 1 - LR = 2^{-\alpha} \quad (2)$$

The progress ratio represents the investment cost declines while the cumulative capacity doubles.

2.2.1. Multiregional learning

Some technologies have obvious regional characteristics [37]. The research, development, use and improvement processes of these