Energy Policy 119 (2018) 97–104

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Carbon overhead: The impact of the expansion in low-carbon electricity in China 2015–2040

Rong Yuan[a,b,*], Paul Behrens[a,c], Arnold Tukker[a,d], João F.D. Rodrigues[a]

[a] Institute of Environmental Sciences, CML, Leiden University, Einsteinweg 2, 2333 CC Leiden, The Netherlands
[b] School of Management and Economics, Tianjin University, Weijin 92, 300072 Tianjin, People's Republic of China
[c] Leiden University College The Hague, Leiden University, Anna van Buerenplein 301, 2595 DG The Hague, The Netherlands
[d] Netherlands Organization for Applied Scientific Research TNO, Anna van Buerenplein 1, 2595 DA The Hague, The Netherlands

ARTICLE INFO

Keywords:
CO_2 emissions
Low-carbon electricity technology
Investment

ABSTRACT

China has embarked on a massive program of low-carbon electricity (LE) deployment, in order to reduce its current dependence on coal. The cumulative installed capacity of LE in 2015 was almost four times of that in 2002. Moreover, China has a target of 20% for non-fossil fuels in primary energy consumption by 2030. LE provides substantial carbon savings in the use phase, but LE infrastructure tends to require more materials than their fossil-fuel electricity counterpart. Here we estimate the carbon 'overhead' from infrastructure expansion during China's transition to LE. We report estimates of the learning curves of the carbon intensity of LE installation, calculated from regional historical data in the period 2002–2012. We combine this information with the predicted cumulative installed capacity from well-known scenarios from national and international bodies. We then project the trends of carbon impacts from LE investments up to 2040. Our results show that, under all scenarios and every year, the annual carbon impact of LE investments never exceeds 4% of China's total carbon emissions, and that the carbon impacts of the expansion in LE infrastructure show either a steady decline or a peak during 2030–2035 before declining further.

1. Introduction

1.1. The importance of low-carbon electricity development

Along with high-speed economic development, China is facing a growing pressure to address increasing carbon emissions (Li et al., 2016). China's total carbon emissions between 1996 and 2013 increased by 219%, with an absolute growth of 6563 Mt (Ye et al., 2017). Currently, China is the largest CO_2 emitter in the world (Liu et al., 2013). Increasing emissions result mainly from an over-dependence on fossil fuels (Wang et al., 2016). In the 14 years between 2002 and 2016, China's electricity generation increased by 264%, with thermal power accounting for around 75% of this growth (CEC, 2017). In order to accommodate future expansion in electricity generation while mitigating carbon emissions, the expansion of low-carbon electricity (LE) became a key focus of China's policy initiatives (He, 2015). The 13th Five-Year Plan proposes specific targets by 2020 of: 340 GW hydropower, 58 GW nuclear power, 210 GW wind power and 110 GW solar power (NEA, 2016). China also promised to increase the share of non-fossil fuels in primary energy consumption to approximately 20% by 2030 (GOV.CN, 2015). This means that China is likely to experience changes in its electricity mix that will result in a high share of LE, and decreasing carbon emissions in the future. Given the scale of these changes, the impact of this increasing LE share needs a robust assessment.

1.2. Current status and future prospects of low-carbon electricity

Although thermal power is still a key component of China's electricity mix, the share of LE in total installed capacity has steadily increased. Fig. 1(a) and (b) show that the cumulative installed capacity of thermal power in China increased by 286% from 2002 to 2015, while the cumulative installed capacity of LE in 2015 was almost four times of that in 2002. Hydropower increased from 86 GW to 320 GW between 2002 and 2015. Nuclear power increased by 6% in the same period, reaching 29 GW in 2015. Since 2007, wind power grew rapidly with an average annual growth of 53% during 2007–2015, reaching 129 GW by 2015. The annual growth rate for solar power varied between 79% and 200% during 2010–2015. In absolute figures, solar power increased from 1 GW in 2010 to 77 GW in 2015.

Given the fast growth of China's LE, much attention has been focused on long-term scenarios for LE development. The International

---

[*] Corresponding author at: Institute of Environmental Sciences, CML, Leiden University, Einsteinweg 2, 2333 CC Leiden, The Netherlands.
E-mail address: r.yuan@cml.leidenuniv.nl (R. Yuan).

https://doi.org/10.1016/j.enpol.2018.04.027
Received 28 January 2018; Received in revised form 10 April 2018; Accepted 14 April 2018

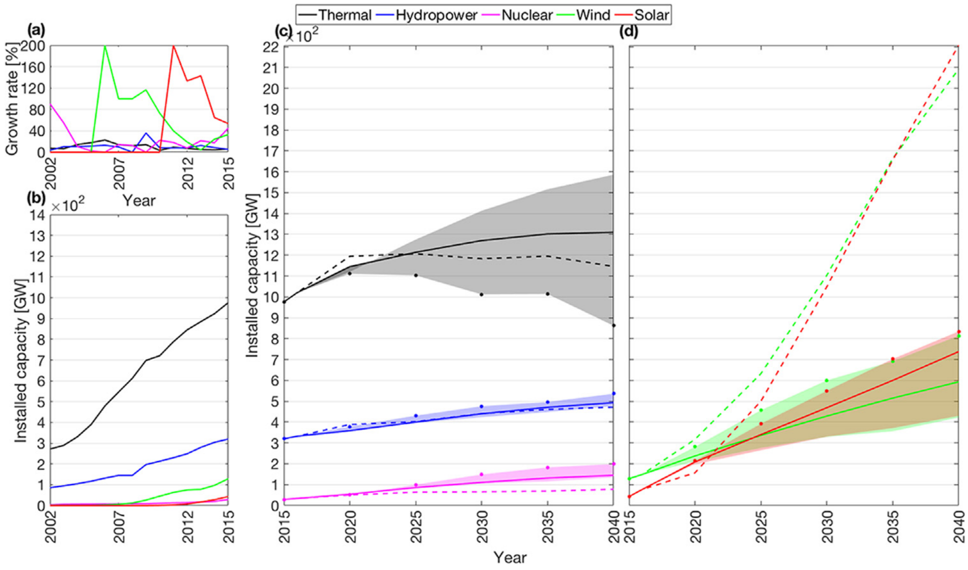

Fig. 1. Growth in installed capacity of electricity technologies according to different scenarios: (a) annual growth rate of installed capacity; (b) historical cumulative installed capacity; (c) projections of thermal, hydro and nuclear power under four scenarios; (d) projections of wind and solar power under four scenarios. Note: solid lines show the projected cumulative installed capacity in the IEA-New scenario, while shades indicate a range of the projection of the IEA-New scenario based on the IEA-Current scenario and IEA-Sustainable scenario. Solid dots show the projected cumulative installed capacity in the IEA-Sustainable scenario. Dashed lines show the projected cumulative installed capacity in the NDRC-High RE scenario. In the legend, color denotes electricity technology. Data sources: *World Energy Outlook* (IEA, 2017, 2016, 2013) and *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study* (NDRC, 2015).

Energy Agency (IEA, 2017, 2016, 2014) reports three scenarios for LE installation in China, assuming Current Policies (IEA-Current), New Policies (IEA-New) and Sustainable Development Policies (IEA-Sustainable). There are also national scenarios developed by the National Development and Reform Commission for High Renewable Energy Penetration (NDRC-High RE) (NDRC, 2015), see Fig. 1(c) and (d). Both these nationally and internationally produced scenarios project changes to 2040. By 2040, the total cumulative installed capacity of LE in China in the IEA-Current, IEA-New, IEA-Sustainable, NDRC-High RE scenarios will reach 1464, 1969, 2384 and 4848 GW respectively, accounting for 48%, 60%, 73% and 81% of the total respectively. The difference in scenarios provided by IEA and NDRC is associated with the growth of wind and solar power. The IEA-Current, IEA-New and IEA-Sustainable scenarios project an expansion of wind power at a growth rate far below the one experienced in 2002–2015, such that wind power in the IEA scenarios reach only 422, 593 and 814 GW by 2040 respectively. Only the NDRC-High RE scenario predicts for wind an average annual growth of 16% through 2040, such that wind power will reach 2092 GW by 2040. The three IEA scenarios predict 72–80% annual growth during 2015–2020, but their initial high growths are expected to slow dramatically to 4–6% for the period 2025–2040. The IEA-Current, IEA-New and IEA-Sustainable scenarios project solar power of 430, 738 and 835 GW by 2040 respectively. However, under the NDRC-High RE scenario, solar power demonstrates spectacular growth after 2025, which will grow 13% annually during 2025–2040 and reach 2.2 TW by 2040. In the IEA-Sustainable and NDRC-High RE scenarios, China will achieve a peak in thermal power capacity by 2035.

1.3. *Related studies of carbon impact of low-carbon electricity in China*

The decarbonization of the Chinese electricity system has attracted substantial research interest. Studies mainly focus on two aspects: impacts of LE expansion on historical carbon emissions (Hong et al., 2013; Dong et al., 2017; Ito, 2017; Mu et al., 2018, Xie et al., 2017, Xie et al., 2018), and prediction of the impact of LE expansion on carbon emissions in the future (Qi et al., 2014; Song et al., 2015; Sun et al., 2016; Pan et al., 2017; Zhao et al., 2017; Furlan and Mortarino, 2018; Liu et al., 2018). Perhaps unsurprisingly, these studies generally conclude that the development of LE will reduce emissions, but several also point out that LE investments tend to require more materials, and might therefore lead to high levels of infrastructure-related emissions (Arvesen and Hertwich, 2012; Amponsah et al., 2014; Hertwich, 2013; Hertwich et al., 2015). Although such emissions related to the expansion of LE infrastructure may be very important in the Chinese energy transition, on this subject there are still few quantitative studies available. Given the importance and scale of this transition, we investigate how the carbon impacts of LE investments will influence China's low-carbon electricity development.

1.4. *Purpose and contributions*

Here we analyze the carbon impacts of LE investments as reflected by the aforementioned energy scenarios for China. We consider four major LE technologies: hydro, nuclear, wind and solar power. We estimate the carbon impact of LE investments on the basis of historic carbon intensity of LE installation, that is the carbon impact of per unit installed capacity of LE ($MtCO_2/GW$). We assess this evolution over the period 2002–2012 using a Multi-Regional Input-Output (MRIO) models discerning the 30 provinces of China. MRIO models allow for the estimation of direct and indirect carbon impacts from LE investments at provincial level in China (Miller and Blair, 2009). By using multiple provincial-level estimates we can provide both a mean and variance of the carbon intensity of different energy types. As carbon intensities of LE installation are found to decrease significantly with increased cumulative installed capacities, we establish experience curves to emphasize the potential of declining carbon intensity of LE installation. Finally, using estimated experience curves, we project carbon impacts of LE investments based on the growth of LE capacity in the four scenarios from IEA and NDRC outlined above.

We provide an evaluation of feasible ranges of carbon impacts LE investments up to 2040 by extrapolating information from historical data. Although we do not draw attention to the effect of LE development on carbon emissions in the operational phase, the integration of carbon impact of LE investments into carbon emissions projections complements the conventional analysis of operational phase emissions. Our analysis also highlights several lessons for other countries attempting to decarbonize their electricity system. This paper proceeds in four parts: Section 2 describes methods and data. Section 3 presents the main results. Section 4 presents a comparison with LCA studies, and an evaluation of uncertainty of projections. Section 5 concludes and outlines relevant policy implications.

2. Methods and data

2.1. *Estimation of historical carbon intensity of installation*

We first estimate the carbon intensity of installation ($MtCO_2/GW$) using the MRIO model. Following the method developed by Hedi