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

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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

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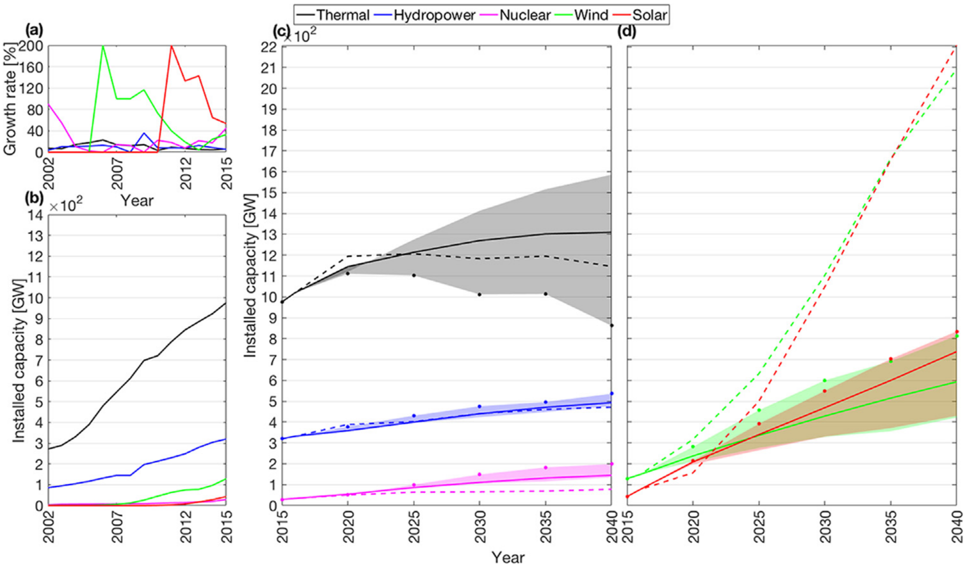

Fig. 1. Growth in installed capacity of electricity technologies according to different scenarios: (a) annual growth rate of installed capacity; (b) historical cumulative installed capacity; (c) projections of thermal, hydro and nuclear power under four scenarios; (d) projections of wind and solar power 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

(2017), electricity investments are mapped against the MRIO table's classifications, and carbon impacts of LE investments are estimated:

$$q = B \times L \times V \times S \tag{1}$$

The MRIO model comprises of n_R regions, each of them with n_S economic sectors. q is the carbon emissions from the investment in a particular electricity technology (Mt); B is a row vector of CO_2 emission coefficients with length $n_R n_S$, showing carbon emissions ($MtCO_2$) per unit of economic output (million yuan) of each sector; $L = (I - A)^{-1}$ is a square Leontief inverse matrix with side of length $n_R n_S$, and in turn A is a matrix of technical coefficients (expressing which inputs from other sectors are required to generate a unit of output of a given sector); V is a diagonal matrix with side of length $n_R n_S$, showing the investment scale of given electricity technology in a region (million yuan); S is an input share vector of length $n_R n_S$, which represents the investment cost structure of a given electricity technology.

Note that the analysis is performed separately for each technology in each region. If a region invested in an electricity technology, the main diagonal elements of V represent the investment scale of given electricity technology in this region, while elements of other regions on the main diagonal of V are all zeros. Moreover, the investment cost structure of each electricity technology is assumed to be identical for different periods and regions.

The carbon intensity of installation for an electricity technology can then be obtained from the new installed capacity of given electricity technology:

$$p_r = q_r / n_r \tag{2}$$

where r is an index referring to one of the 30 provinces, p is the emissions per unit of installed capacity ($MtCO_2$/GW); and n is the amount of new installed capacity (GW).

2.2. Projection of carbon intensity of installation

In order to evaluate the general performance of carbon intensities of installation for an electricity technology, we calculate the median and 95% confidence intervals of the carbon intensity of installation, p_r, using the 30 provinces as a sample, weighted by provincial installed capacity. Then, we extrapolate these experience curves to provide estimates of future carbon intensities. The relation between carbon intensity of installation and cumulative installed capacity is described by the experience curve (Samadi, 2018):

$$p_m = p_1 \times C^{-a} \tag{3}$$

where p_m is the carbon intensity of installation for the m units of an electricity technology, p_1 is the carbon intensity of installation for the first unit of a given electricity technology; C is the total cumulative installed capacity of a given electricity technology in China; $-a = log_2(1 - l)$ is experience index of a given electricity technology, showing the decrease in carbon intensity of installation as a function of increased cumulative installed capacity; and l is the experience rate of a given electricity technology.

Since Eq. (3) is in an exponential form, the experience elasticity a can be converted to a linear function in a log scale (Zou et al., 2016):

$$log(p_m) = log(p_1) + a \times log(C) \tag{4}$$

After estimating the slope of the linear function a, we can extrapolate the carbon intensity of LE installation for future cumulative installed capacities as suggested from the four IEA and NDRC scenarios (see Fig. 1). Since our approach for calculating the carbon intensity of LE is using an MRIO model, in principle carbon reductions in the supply chain of the LE infrastructure (e.g. in the electricity sector itself) could also impact the experience curve. We will discuss this matter in more detail in Section 4.2, clarifying the relevance of this effect.

2.3. Scenario analysis for carbon impacts of LE investments

Since the IEA and NDRC report the total cumulative installed capacity in China for five-year blocks until 2040, we obtain new installed capacity of LE in these five-year periods rather than each individual year. Thus, we project a range for the carbon impact of LE investments for each period by assuming that the carbon intensity is at the starting or last year of the projection. Mathematically, the upper (q^{upper}) and lower (q^{lower}) bound of carbon impacts of LE investments for a period is calculated as:

$$q^{upper} = n \times p^{start} \tag{5-1}$$

$$q^{lower} = n \times p^{last} \tag{5-2}$$

where n is the projected new installed capacity of a LE technology for given period, and p^{start} and p^{last} is the projected carbon intensity of installation of a given electricity technology in the starting and last year of given period respectively.

2.4. Data

The MRIO tables of China's 30 provinces for 2002, 2007, 2010, 2012 are obtained from Shi and Zhang (2012), Liu et al. (2012), Liu et al. (2014) and Mi et al. (2017), respectively. The 30 sectors listed in 2007, 2010 and 2012 tables and the 21 sectors listed in the 2002 table are aggregated to 21 sectors to obtain consistent tables for 2002, 2007, 2010 and 2012 (as shown in Table A1 in Appendix). We use official data, including the history of cement production and the consumption of energy and electricity, to estimate sectoral CO_2 emissions. We consider carbon emissions from cement production because cement is emissions-intensive, and is a major input in the construction of some energy types including hydropower and nuclear (less so for wind, and very minor for solar). We adopt the IPCC (2006) sectoral approach to calculate CO_2 emissions. CO_2 emissions equal activity data (fossil fuel consumption and cement production) multiplied with carbon emission factors. The activity data of fossil fuels for 2002, 2007, 2010 and 2012 are collected from the Provincial Energy Balance Tables reported by the *China Energy Statistics Yearbook* (National Bureau of Statistics of China (NBS), 2003a, 2008a, 2011a, 2013a). Since the Provincial Energy Balance Tables of China only supply regional fossil fuel consumptions at an aggregated sectoral level, the data of sub-sectoral fossil fuels consumption are from the Provincial Statistical Yearbooks of China's 30 provinces (NBS, 2003c, 2008c, 2011c, 2013c). The data of the annual cement production are collected from the *China Statistical Year book* (NBS, 2003b, 2008b, 2011b, 2013b). Carbon emission factors for fossil fuels (tonne CO_2/ tonnes, m^3) and cement production (tonne CO_2/ tonnes) are collected from report of the IPCC (2006) and NDRC (2011). Electricity investment data comes from the *China Electric Power Yearbook* (CEPYEB, 2003, 2008, 2011, 2013) and *Annual development report of China's power sector* (CEC, 2003, 2008, 2011, 2013). The total cumulative installed capacity of each electricity technology in China are from the *China Electric Power Yearbook* (CEPYEB, 2003, 2008, 2011, 2013). The investment structure of LE refers to Dai et al. (2016), and the data for thermal power is collected from the *Cost and Performance Baseline for Fossil Energy Plants* (NETL, 2010). The projected data of cumulative installed capacity are collected from the *World Energy Outlook* (IEA, 2017, 2016, 2013) and *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study* (NDRC, 2015). The detailed installed capacity schedule for each five-year from 2015 to 2040 is reported by the NDRC, while the IEA estimates for 2020 and 2035 are absent in the 2017 report. Since estimates for such years exist in the IEA reports of 2013 and 2016, we use linear interpolation to adjust the projection of IEA (2013) and 2016 so that successive reports between 2015 and 2040 can be obtained.

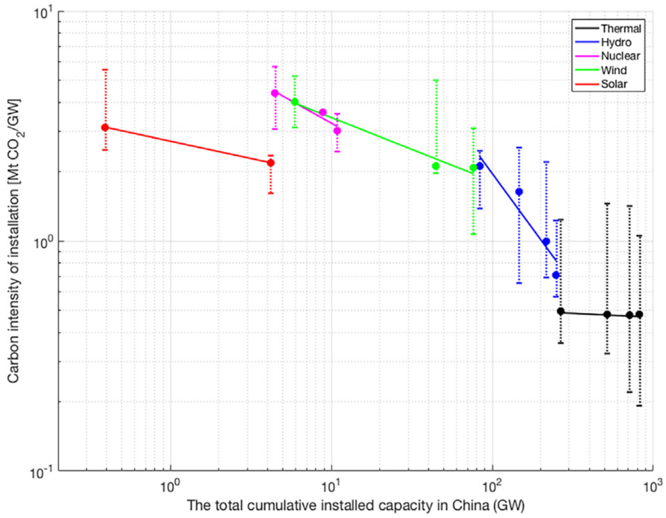

Fig. 2. Experience curves for LE technologies. Solid lines reflect resulting experience curves for different electricity technologies based on linear regression of the data. Dots represent median estimates. Error bars represent 95% confidence interval estimates. In the legend, color denotes electricity technology. Data sources: authors' own elaboration.

3. Results

3.1. Historical carbon intensity of LE installation

Fig. 2 shows the median value and variability of 30 provincial-level estimates of carbon intensity of installation depending on the China's total cumulative installed capacity in 2002, 2007, 2010 and 2012. Fig. A1 contains the corresponding results for the carbon intensity of LE installation in 30 provinces during 2002–2012. The result shows little variation in the median of carbon intensity of thermal power installation with increased cumulative installed capacity, being stable at 0.48–0.50 $MtCO_2/GW$. However, there is a clear downward trend for carbon intensity of LE installation. For example, the median of hydropower installation carbon intensity decreased from 2.12 to 0.71 $MtCO_2/GW$ during 2002–2012, when cumulative installed capacity of hydropower increased from 83 GW in 2002 to 249 GW in 2012. Using the experience curve model, Fig. 2 also plots the relationship between the median for carbon intensity of installation and China's total cumulative installed capacity. Table A2 shows that correlation coefficients, indicating the robustness of the estimated experience curves, are high for all LE technologies ($R^2 > 95\%$). Using the derived experience curves, we project future carbon intensities of LE installation during 2015–2040 based on increased cumulative capacity in China under the four scenarios from IEA and NDRC, see Table A3.

3.2. Outlook for carbon impacts of LE investments

Fig. 3(b) shows the projected carbon impacts of LE investments up to 2040. For the in-depth assessment of carbon implication of future LE investments (details are shown in Table A4), we also compare projected carbon impact of LE investments with the projection of China's total carbon emissions up to 2040, as reported by the IEA and NDRC (see Fig. 3(a)). In the IEA-Current and IEA-New scenarios, the cumulative carbon impact of LE investments during 2015–2020 is 377 Mt and 423 Mt respectively. Since Fig. 3(a) shows China's total carbon emissions in a particular year, a more useful measurement is the annualized carbon impact of LE investments. Under the IEA-Current and IEA-New scenarios, the average annual carbon impact of LE investments during 2015–2020 is 75 Mt and 85 Mt respectively. Thus, the share of average annual carbon impact of LE investments for the period of 2015–2020 relative to China's total carbon emissions in 2020 under the IEA-Current and IEA-New scenarios is 0.81% and 0.93% respectively. The

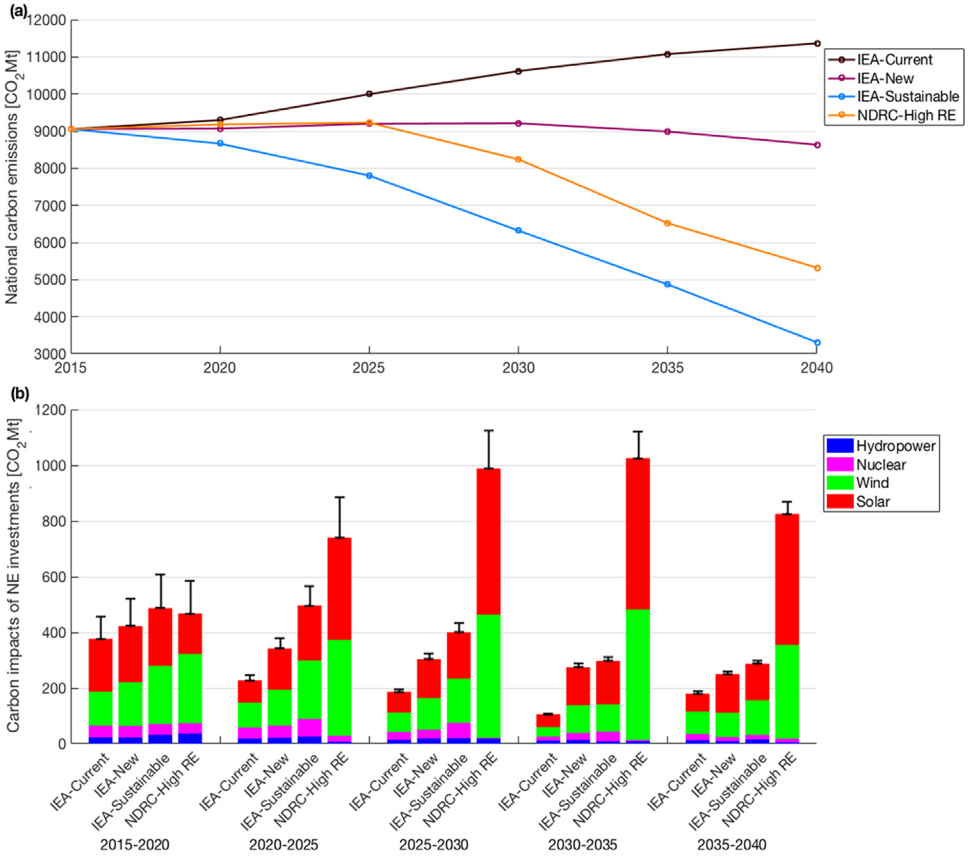

Fig. 3. Carbon impacts of LE investments during 2015–2040: (a) total carbon emissions in China during 2015–2040 from IEA and NDRC scenarios; (b) estimated cumulative carbon impacts of LE investments for each 5-year period of 2015–2040. That is, each tick across the x-axis shows a 5-year period, with each of the stacked bars, and the y-axis showing the total emissions over that 5-year period. Note: stacked bar charts indicate projected carbon impacts of LE investments based on carbon intensity of LE installation in the last year during each period, which is the lower bound of results. Error bars show the difference between upper and lower bound in the carbon impact of LE investments as described in the Methods. Data sources: data for Fig. 3(a) are from the *World Energy Outlook* (IEA, 2017, 2016, 2013) and *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study* (NDRC, 2015); data for Fig. 3(b) are from authors' own elaboration.

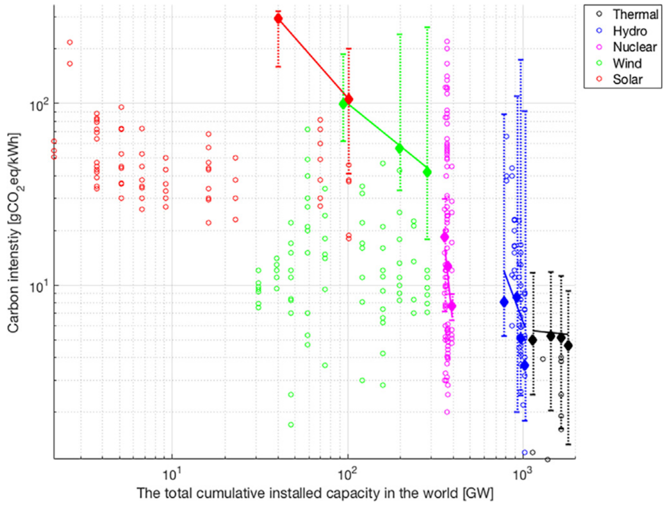

Fig. 4. Summary of life-cycle emissions from different electricity technologies based on global cumulative installed capacity over the period 2002–2012. Note: solid dots represent individual estimates from the literature. Since power generation is the major contributing sub-stage to carbon emissions for thermal power, reported total life-cycle emissions of thermal power are replaced with carbon emissions in the infrastructure phase. Error bars indicate the range of our estimated 30 provinces' carbon intensity of installation. Diamonds reflect the median of carbon intensity of installation. Color in legend indicates the electricity technology. Data sources: data for life-cycle emissions from different electricity technologies can be seen in the reference of Appendix; data for global cumulative installed capacity are from the *World Energy Outlook* (IEA, 2017, 2016, 2013) and *Global Wind Energy Council* (GWEC, 2016).

cumulative carbon impact of LE investments for the period of 2035–2040 in IEA-Current and IEA-New scenarios decreases to 180 Mt and 250 Mt respectively. Similar to the above measurement, the average annual carbon impact of LE investments during 2035–2040 under the IEA-Current and IEA-New scenarios is 40 Mt and 50 Mt, respectively, which account for 0.32% and 0.58% of China's total carbon emissions in 2040, respectively. In comparison with IEA-Current and IEA-New scenarios, the annual average carbon impact of LE investments in IEA-Sustainable and NDRC-High RE scenarios are a larger component of China's total carbon emissions. In the IEA-Sustainable and NDRC-High RE scenarios, the annual carbon impact of LE investments for the period 2015–2020 is 98 Mt and 94 Mt, respectively, accounting for 1.13% and 1.02% of China's total carbon emissions in 2020, respectively. By 2040, the annual carbon impact of LE investments for the period 2035–2040 relative to China's total carbon emissions under the IEA-Current and IEA-New scenarios increases to 1.74% and 3.10%, respectively. Generally, in all scenarios and every year, the annual carbon impact of LE investments never exceeds 4% of China's total carbon emissions.

3.3. Differences among projections under four scenarios

Fig. 3 also shows the differences among projections under four scenarios. In the IEA-Current scenario, China's total carbon emissions will rise gradually, stabilizing at 11,364 Mt by 2040, while China's total carbon emissions in the IEA-New scenario peaks at 9212 Mt in 2030 and then declines to 8633 in 2040. In the IEA-Sustainable and NDRC-High RE scenarios, China's total carbon emissions reduce by 63% and 41% from 2015 to 2040 respectively. China's total carbon emissions in the NDRC-High RE scenario is higher than IEA-Sustainable scenario although wind and solar power will grow fast in the NDRC-High RE scenario. This is because the cumulative capacity of thermal power in the NDRO-High RE scenario is significantly larger than in the IEA-Sustainable scenario (see Fig. 1). The carbon impact of LE investments in the NDRC-High RE scenario is larger than that of other scenarios. The carbon impact of LE investments in the IEA-Current, IEA-Policy and IEA-Sustainable scenarios show a downward trend, falling by 59%, 50% and 51% between the 2015–2020 period and the 2035–2040 period. In the NDRC-High RE scenario, from 2015 to 2035, the carbon impact of LE investments shows a sharp growth, while the carbon impact of LE investments reaches a peak during 2030–2035 (1021 Mt), after which it gradually declines to 826 Mt during 2035–2040. Overall, for all scenarios, during 2035–2040, the continuous increase in LE is expected to bring the most significant declines in carbon emissions while the carbon impact of LE investments drops.

4. Discussion

4.1. Comparison with results from LCA studies

The carbon impact of LE investments also can be estimated using Life Cycle Assessment (LCA). LCA can addresses emissions associated from the construction plant and the dismantling of a plant (Suh and Huppes, 2005; Crawford et al., 2018). To assess the carbon impact of LE investments, several researchers have performed systematic reviews and harmonization of LCA studies by establishing a compatible set of system parameters and a standard methodology (Hsu et al., 2012; Hyung et al., 2012; Menten et al., 2013; Hertwich et al., 2015; Atse et al., 2016). These studies provide estimates of average life-cycle emissions (Asdrubali et al., 2015), the distribution of life-cycle emissions over life-cycle stages (Turconi et al., 2013), and the factors influencing results of LCAs (Raadal et al., 2011; Warner and Heath, 2012). However, there are challenges in clarifying the carbon impact of LE investments in China using such harmonized data. Since the accuracy of LCA is dependent on geographical factors (Ding et al., 2017), assessments generally require China-specific values. However, most LCA studies in China focus only on recent years (solar: Fu et al., 2015, Yang et al., 2015, Xu et al., 2018b, wind: Xue et al., 2015, Xu et al., 2017a, nuclear: Ou et al., 2011, Jiang et al., 2015, and hydro: Hu et al., 2013, Pang et al., 2015, Li et al., 2017), and with limited number of China's LCAs available for low-carbon electricity in each year. Thus, a review of China's LCA studies covering a short period cannot reflect the dynamic of carbon intensity of installation well. Moreover, most LCA studies for China only assess carbon emissions per unit of LE generation (gCO$_2$/kWh), while the infrastructure-related emissions are rarely separately reported in LCAs.

Comparing our estimates of carbon intensity of LE installation with LCA studies can give further insights, as infrastructure is the major contributing sub-stage to LE's life-cycle emissions (Lenzen and Munksgaard, 2002; Warner and Heath, 2012; Turconi et al., 2013). Since we analyze carbon emissions induced by electricity investments (MtCO$_2$/GW) and LCAs often report the carbon emissions per kWh of generated electricity (gCO$_2$/kWh), we converted the carbon intensity of installation to the appropriate unit (see the methods in Appendix). Fig. 4 shows a comparison with life-cycle emissions of LE from published LCA studies (data see Table A5-A9). Since the LCA case studies included in the Fig. 4 are not only from China but also from other countries the cumulative installed capacity refers not to capacity in China alone but in the whole globe. The downward-sloping trend of LE's life-cycle emissions in Fig. 4 is in line with our results, confirming that carbon impacts of LE investments have a good correlation with cumulative installed capacity. Moreover, our estimates for thermal, hydro, nuclear and wind power are close to results of LCA studies. However, our estimates for solar power are higher than the corresponding results of LCA studies. This may be because the manufacturing process of solar systems in China could result in more emissions than the same processes in other countries, as China's electricity generation is highly dependent on coal (Peng et al., 2013; Nugent and Sovacool, 2014). Generally, our estimates are within the range of results from LCA studies.

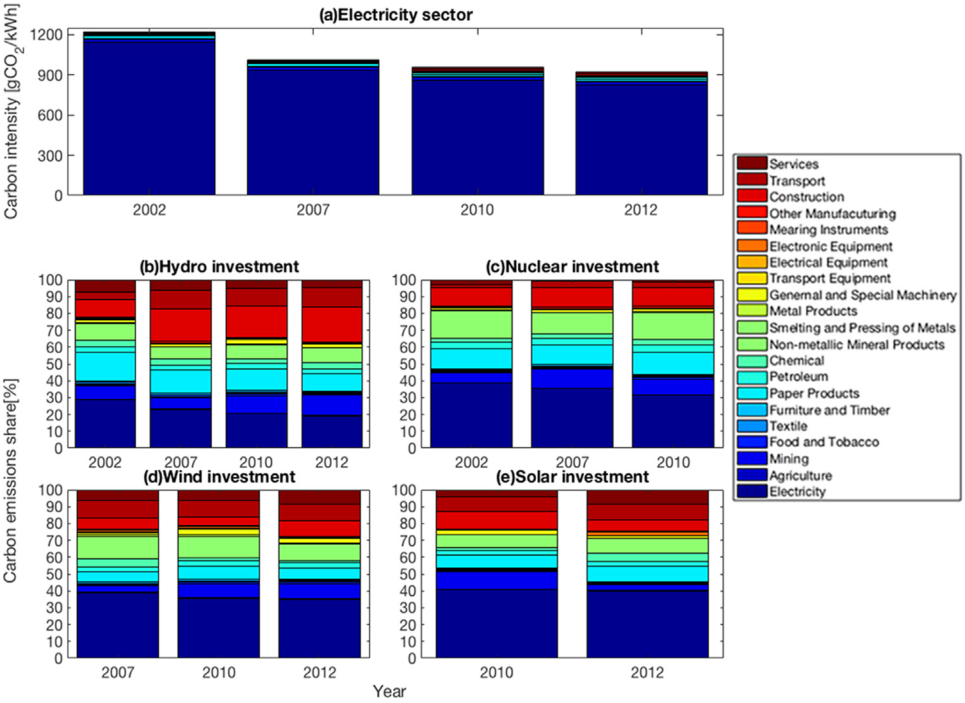

Fig. 5. The evolution of carbon impact of electricity sector: (a) the evolution of carbon intensity of electricity generation (gCO$_2$/kWh); (b)-(e) the contribution of electricity sector to the total carbon impact of LE investments (%). Data sources: authors' own elaboration.

4.2. Evaluating the uncertainties of the projection

The experience curve (or learning curve) describes the way that performance, such as lowering material inputs, costs, and emissions, develops as industries gain more experience through producing products. Since it is based on the amount of product made, performance increases are taken from the perspective of cumulative capacity and the carbon intensity of LE installation. Due to the empirical, rather than analytical, nature of experience curves, cumulative capacity is only one of several explanations for the reduction of carbon intensity of installation. Therefore, extrapolations are subject to the uncertainties underlying the derived experience rates (Fukui et al., 2017). Our analysis does not allow for the feedbacks whereby increasing LE investments result in an electricity system with lower carbon emissions: in reality any declines in the carbon intensity of LE investments would decrease the carbon intensity of electricity generation which would create a feedback for further emission reductions. In order to better put our experience curve into perspective, we discuss the effect of electricity system itself on LE investments in the future. We find that given the reduced carbon intensity of electricity generation, during 2002–2012 (see Fig. 5(a)), the contribution of electricity sector to carbon impact of LE investments gradually declined (see Fig. 5(b)-(e)). This means that the experience curves could have a role to play in decarbonizing electricity sector due to learning investments bringing down the environmental costs of LE installation. Thus, the reduction of carbon intensity of LE installation with increased cumulative capacity could be amplified by the improvement of carbon performance of electricity sector. We hypothesize that the actual carbon impacts of LE investments from 2015 to 2040 could be lower than the estimated results, if this effect would be taken into account. However, from Fig. 5(a), we also can find that the decline has flattened, and the carbon intensity of generation in 2012 is almost similar to the value of 2010. This may indicate that there is minimal room left for this additional feedback loop effect of electricity system on LE investments as not much more experience can be acquired in the relatively stable electricity system. Thus, although the emission reduction of electricity system influences the extrapolation of the experience curve, it will offer a small opportunity for continued decline in the carbon intensity of LE installation. Therefore, the change of electricity system is not explicitly taken into account in experience curve analysis.

5. Conclusions and policy implications

Although LE provides more carbon savings in the operational phase than fossil-fuel electricity, LE infrastructure tends to require more materials than their fossil-fuel electricity counterpart. In order to estimate carbon overhead from infrastructure expansion, we project the carbon impact of LE investments up to 2040. We find that in the IEA-Sustainable and NDRC-High RE scenarios, the development of LE will lead to large emission reductions, but the carbon impact of LE investments will also account for a certain share of China's total carbon emissions. In the IEA-Sustainable and NDRC-High RE scenarios, the average annual carbon impact of LE investments relative to China's total carbon emissions will increase to 1.74% and 3.10% during 2035–2040 from 1.13% and 1.02% during 2015–2020 respectively. The carbon impacts of LE investments in all IEA scenarios show a steady declining trend. The NDRC-High RE scenario shows a larger carbon impact of LE investment than IEA scenarios with the rapid development of wind and solar power. However, the carbon impact of LE investments in the NDRC-High RE scenario will reach a peak during 2030–2035. The carbon impact of LE investments in all scenarios will perform in a similar way during 2035–2040, reaching their lowest level in that period. In conclusion, the future expansion of LE infrastructure will not pose a significant threat to carbon emissions when compared with the emission reductions brought about by LE expansion, and will allow the present declining tendency of China's carbon emissions to persist.

Based on the above conclusions, policy makers can have more information to make a comprehensive action plan for LE development. During 2035–2040, according to all scenarios we will see large reductions in carbon impact of LE investment. Evidently, scaling up deployment of LE will eventually contribute towards a more sustainable electricity sector. Moreover, the carbon impact of LE investments will take up a small percentage of China's total carbon emissions in all scenarios (less than 4%). This indicates that, the carbon overhead from

LE infrastructure expansion is small, in a relative sense, compared to total CO_2 emissions. Thus, the carbon impact of LE investments cannot be used as an argument to suggest halting LE expansion in China. The implication from this Chinese case study provides lessons for other countries which are also faced with an energy transition towards LE. Previous studies have showed that the infrastructure phase of LE has higher carbon impacts and so have recommended the development of environmentally-sound infrastructure to mitigate this (e.g. the context of Ontario (Siddiqui and Dincer, 2017) and European Union (Bonou et al., 2016)). We encourage other researchers to consider similar efforts, and to analyze opportunities for the expansion of LE infrastructure in other countries. Furthermore, if climate policies can be implemented based on LE development goals under the IEA-Sustainable scenario, China will face significant emission reductions in the future, with small carbon impacts of the expansion of the infrastructure. Finally, we also discussed the uncertainty of the projection using experience curves derived from estimates herein, and from the literature. Although the emission reductions in the electricity system has limited effects on the extrapolation of the experience curve, the operational impact of LE development in the future needs to be explored. Thus, future research could give more insights by providing ex-ante projections of the operational impact of LE development.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2018.04.027.

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