Hidden Benefits of Electric Vehicles for Addressing Climate Change

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There is an increasingly hot debate on whether the replacement of conventional vehicles (CVs) by electric vehicles (EVs) should be delayed or accelerated since EVs require higher cost and cause more pollution than CVs in the manufacturing process. Here we reveal two hidden benefits of EVs for addressing climate change to support the imperative acceleration of replacing CVs with EVs. As EVs emit much less heat than CVs within the same mileage, the replacement can mitigate urban heat island effect (UHIE) to reduce the energy consumption of air conditioners, benefitting local and global climates. To demonstrate these effects brought by the replacement of CVs by EVs, we take Beijing, China, as an example. EVs emit only 19.8% of the total heat emitted by CVs per mile. The replacement of CVs by EVs in 2012 could have mitigated the summer heat island intensity (HII) by about 0.94°C, reduced the amount of electricity consumed daily by air conditioners in buildings by 14.44 million kilowatt-hours (kWh), and reduced daily CO_2 emissions by 10,686 tonnes.

The replacement of CVs by EVs has been an inevitable trend around the world. As of December 2013, there were 405,000 highway-capable plug-in electric passenger cars and utility vans worldwide[1]. An increasingly hot debate on whether the replacement of CVs by EVs should be delayed or accelerated has surfaced among researchers, enterprises, and governments[2], since EVs are more costly and cause more pollution than CVs in the manufacturing process[3,4].

UHIE is influential in metropolitan areas[5]. For example, the surface temperatures in some urban areas of Beijing, on July 5, 2010, were nearly 50°C[6,7]. UHIE, which contributes to the extremely high temperatures in urban areas, is the main cause of this phenomenon.

UHIE would cause huge air-conditioning energy consumption[8–10]. The positive feedback of air-conditioning energy consumption to UHIE was proposed and evaluated in Refs. 11–13. Heat emitted by vehicles and air conditioners in buildings, the main source of anthropogenic heat emissions in urban areas, is one of the main causes of UHIE[14]. The strength of UHIE is measured in terms of HII[15]. HII is calculated as the urban temperature minus the rural temperature, which depends on heat emissions, aerosol pollution, underlying ground surface, and ventilation, etc.

The replacement of CVs by EVs has important implications for UHIE. There is no doubt that CVs will be replaced by EVs in the long run because fossil energy is non-renewable. However, there is an increasingly hot debate on whether the replacement should be delayed or accelerated[2]. Here we reveal two hidden benefits of EVs for addressing climate change to support the acceleration of the replacement. EVs emit much less heat than CVs within the same mileage. Therefore, the replacement can mitigate HII, which can reduce the amount of electricity consumed daily by air conditioners, benefitting the local and global climate. These effects are shown in Fig. 1, and Beijing in the summer of 2012 is taken as an example.

Results

Heat emissions ratio of EVs to CVs. In Beijing in 2012, the average heat emissions by CV and EV per mile were estimated to be 6.31 and 1.25 million joules (J) respectively. Then the average heat emitted by EV per mile was about 19.8% of that by CV.

Reduction of heat emissions. In the summer of 2012 in Beijing, the daily heat emitted by CVs was 9.85×10^{14} J. If CVs were replaced by EVs, the heat emitted by EVs would be reduced by 7.90×10^{14} J, and the heat emitted by power plants would be increased by 6.09×10^{13} J, so the total daily reduction of heat emissions would be 7.29×10^{14} J.
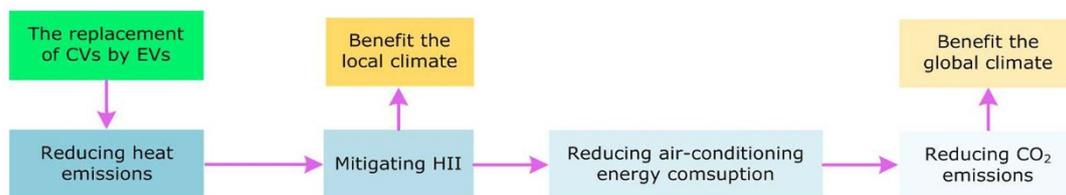
Figure 1 | The two hidden climate benefits of replacing CVs with EVs. EVs emit much less heat than CVs within the same mileage. Replacing CVs with EVs would mitigate HII and CO_2 emissions to benefit local and global climates.

HII mitigation and reduction of air-conditioning energy consumption and CO_2 emissions. The average HII was estimated at 3.0°C in the summer of 2012 in Beijing. Heat emissions, which are mainly caused by vehicles and air conditioners in buildings, contributed about half of the HII in Beijing[16]. The daily heat emitted by air conditioners was 4.32×10^{14} J. The decreased heat emissions from the replacement are 1.69 times higher than the emissions of air conditioners in buildings, which would mitigate the summer HII by about 0.94°C (Fig. 2). Because of the reduction of HII, the energy consumed by air conditioners in buildings would decrease by 12.03%. The amount of daily energy that could be saved is 14.44 million kWh, which could reduce CO_2 emissions by 10,686 tonnes per day (Fig. 2). The results are described in Fig. 2.

Discussion

Air conditioners used in vehicles are dispersed, and the energy consumed by them is difficult to calculate. The energy saving and CO_2 emissions reduction are underestimated, but the benefits are still very remarkable.

According to the definition of specific heat capacity, when specific heat capacity is a constant, temperature variation is proportional to the heat variation. According to Ref. 17, at standard atmospheric pressure, the specific heat of dry air is 1.005 kJ/(kg × °C) at temperatures ranging from 0°C to 60°C. The average temperature in summer of Beijing is about 24.6°C[18], so the specific heat capacity of air could almost be regard as a constant in our model. Thus, it is reasonable to assume that the relationship between heat emissions and HII is linear.

There are many reasons for UHIE, three of which are identified as critical factors: the difference in heat emissions, more aerosol particles and different thermal properties of the ground surfaces. It has been found that pollution aerosols have a positive impact on HII in some places[19], while some other studies have found that aerosols have a negative impact on HII[20]. The impact of aerosol particles on HII is also highly non-linear and uncertain[21], therefore, they are not taken into consideration in this model. As to the third factor, the replacement of CVs by EVs is a virtual replacement, which does not change the ground surfaces of Beijing, the thermal properties of the ground surfaces are regarded as unchanged in our model.

Methods

The methods used in this research are summarized in Fig. 3.

First, we analysed the decreased heat emissions caused by the replacement of CVs with EVs. Second, based on the statistics of the contribution of air conditioners in buildings to UHIE and the assumed linear relationship between heat emissions and HII, we deduced the impact of anthropogenic heat emissions on HII. Finally, according to the impact of HII changes on air-conditioning consumption in buildings, we achieved the decreased air-conditioning energy consumption by the replacement.

Heat emissions ratio of EVs to CVs. Energy consumed by CVs is all converted to heat and eventually emitted to the air. Engines of CVs convert fuel energy into thermal and mechanical energy. Then the mechanical energy is converted to heat by overcoming mechanical friction, wind and tire rolling resistance. Energy consumed by EVs is also converted to heat eventually.

In Beijing, the average fuel economy of light-duty vehicles was estimated to be 20.6 miles per gallon in 2012[12]. The heat emitted by gasoline combustion per gallon is 130 million J[22]. Therefore, the average heat emitted by CVs per mile would be:
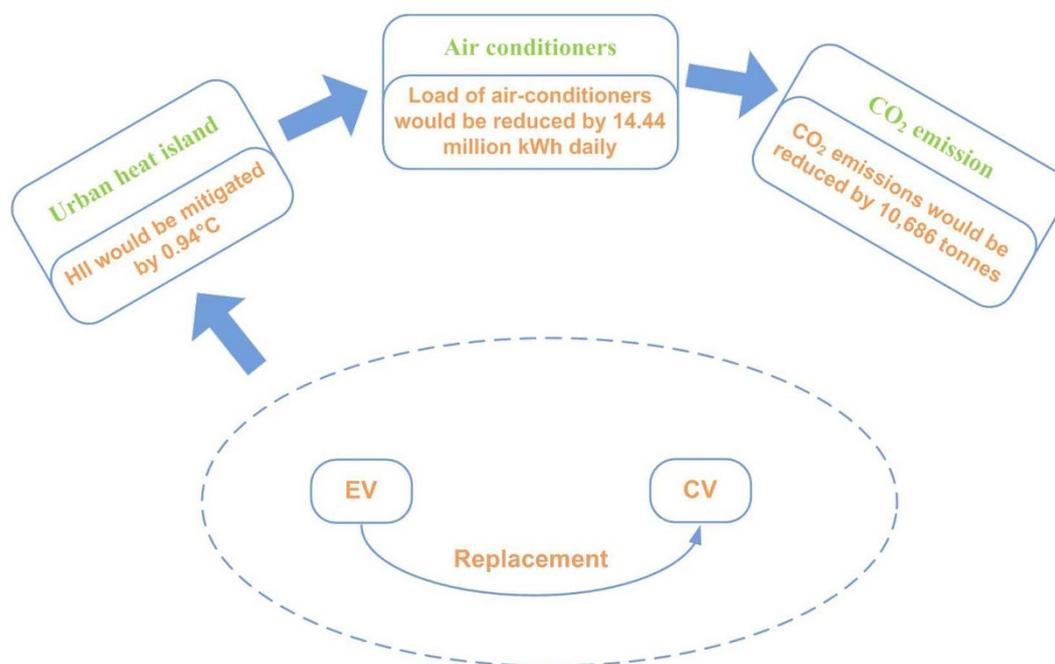

Figure 2 | Overview of the benefits of replacing CVs with EVs. HII would be mitigated by 0.94°C, 14.44 million kWh electricity would be saved daily in summer, and about 10,686 tonnes of CO_2 emissions would be eliminated.

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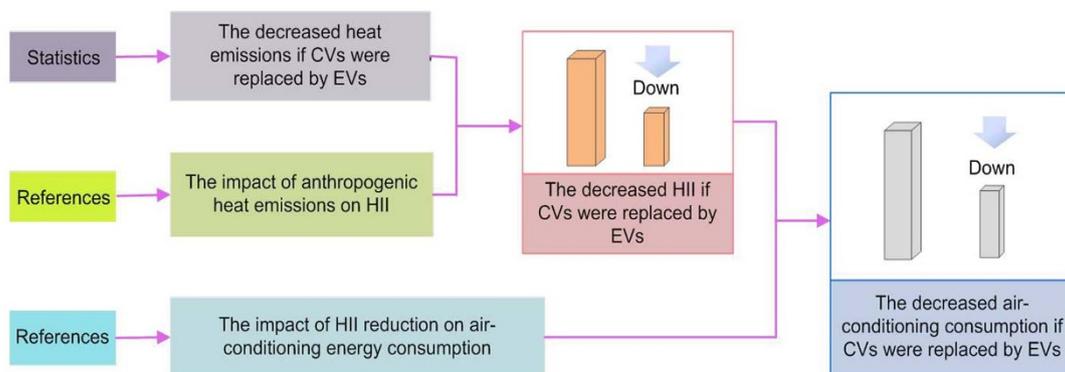
Figure 3 | Diagram of the methods. The data source and procedure of reasoning and estimating are presented. CVs, conventional vehicles; EVs, electric vehicles; HII, heat island intensity.

$$P_1 = \frac{1}{E_1} \times Q_1 = \frac{1}{20.6} \times (130 \times 10^6) = 6.31 \times 10^6 \,(\text{J}) \tag{1}$$

where P_1 is the heat emissions per mile by a CV, E_1 is the fuel economy, Q_1 refers to the energy contained in a gallon of gasoline.

The electricity consumed by an EV per mile in China ranges from 18 kWh to 25 kWh per 100 kilometres for different models[23], and the average is estimated at 0.346 kWh per mile. 1 kWh is equal to 3.6 million J. The heat emitted by an EV per mile would be:

$$P_2 = E_2 \times Q_2 = 0.346 \times (3.6 \times 10^6) = 1.25 \times 10^6 \,(\text{J}) \tag{2}$$

where P_2 is heat emissions per mile by an EV, E_2 is the electricity per mile consumed by an EV, and Q_2 is the energy contained in 1 kWh.

According to equations (1) and (2), heat emitted by EVs per mile is 19.8% of that by CVs, as shown in equation (3):

$$r = \frac{P_2}{P_1} = \frac{1.25}{6.31} \times 100\% = 19.8\% \tag{3}$$

where r is the ratio of heat emitted by EVs to that by CVs.

Increment of heat emissions by power plants in Beijing. In 2012, the total electricity consumption of Beijing was 87,430 million kWh. About 28,312 million kWh was generated by thermal power plants in Beijing, accounting for 32.38% of the total electricity consumption[24]. In 2012, there were 5.2 million vehicles in Beijing[25], and the average daily driving distances were 30 miles[23]. If CVs were replaced by EVs, the increment of electricity produced by thermal power plants (ΔE) in Beijing would be:

$$\begin{aligned}\Delta E &= N_1 \times L \times E_2 \times e = (5.2 \times 10^6) \times 30 \times 0.346 \times 32.38\% \\ &= 1.75 \times 10^7 \,(\text{kWh})\end{aligned} \tag{4}$$

where N_1 is the number of vehicles in Beijing in 2012, L is the average daily driving miles, and e is the ratio of electricity generated by thermal power plants in Beijing to the total electricity consumption of Beijing.

According to the statistics from Ref. 26, when 1 kWh is produced by Beijing's thermal power plants in 2012, the heat emissions would be 3.48×10^6 J. Thus, if CVs were replaced by EVs, the increment of heat emissions by thermal power plants (H_1) in Beijing would be:

$$H_1 = \Delta E \times h_1 = 1.75 \times 10^7 \times 3.48 \times 10^6 = 6.09 \times 10^{13} \,(\text{J}) \tag{5}$$

where h_1 is the heat emissions from Beijing's thermal power plants when 1 kWh is produced.

Reduction of heat emissions. In Beijing in 2012, the daily heat emitted by CVs (H_2) was as following.

$$H_2 = N_1 \times L \times P_1 = (5.2 \times 10^6) \times 30 \times (6.31 \times 10^6) = 9.85 \times 10^{14} \,(\text{J}) \tag{6}$$

In the summer of 2012, the average load of air conditioners in buildings was approximately 5 million kW[27]. Therefore, the daily heat emitted by air conditioners (H_3) in buildings was:

$$H_3 = P_5 \times N_2 \times Q_2 = (5 \times 10^6) \times 24 \times (3.6 \times 10^6) = 4.32 \times 10^{14} \,(\text{J}) \tag{7}$$

where P_5 is the average load of air conditioners and N_2 is the number of hours per day.

If CVs were replaced by EVs, the reduction of daily heat emitted by vehicles (H_4) would be as following.

$$H_4 = H_2 \times (1 - r) = (9.85 \times 10^{14}) \times (1 - 19.8\%) = 7.90 \times 10^{14} \,(\text{J}) \tag{8}$$

If CVs were replaced by EVs, more electricity would be consumed. This would increase power plants' heat emissions in Beijing. Therefore, the total daily reduction of heat emissions (H_5) is calculated as follows.

$$H_5 = H_4 - H_1 = 7.90 \times 10^{14} - 6.09 \times 10^{13} = 7.29 \times 10^{14} \,(\text{J}) \tag{9}$$

HII mitigation. The average HII was 2.77°C during the summer of 2005 in Beijing[28] and 2.90°C in 2009[29]. The data in 2012 are not available from official statistics or academic papers. According to the growth rate of HII from 2005 to 2009, we estimated HII to be 3.0°C in 2012. Heat emissions, mainly caused by vehicles and air conditioners in buildings, contributed to about half of the HII in Beijing[16]. Therefore, if CVs were replaced, in 2012 in Beijing the decreased heat emissions would reduce HII by:

$$\Delta \text{HII} = \text{HII} \times k_1 \times \frac{H_5}{H_3 + H_5} = 3.0 \times 0.5 \times \frac{7.29}{4.32 + 7.29} = 0.94 \,(\text{°C}) \tag{10}$$

where ΔHII is the decreased HII resulting from the decreased heat emissions with the replacement and k_1 is the contribution of heat emissions to HII in Beijing.

Reduction of air-conditioning energy consumption. If HII were to decrease by 1°C, the energy consumed by air conditioners in buildings would decrease by 12.8% during the summer in Beijing[11]. Although the estimation in Ref. 16 is based on data from Beijing in 2005, air-conditioning energy consumption has taken an increasing proportion of total energy consumption in recent years[23], which ensures the validity of our estimation. The reduction of HII resulting from the replacement is near 1°C. We assume the reduction of HII and air-conditioning energy saving is a linear relationship. If CVs were replaced by EVs, during the summer in Beijing, the energy consumed by air conditioners in buildings would decrease by:

$$k_2 = \Delta \text{HII} \times 12.8\% = 12.03\% \tag{11}$$

where k_2 is the percentage of the decreased energy consumed by air conditioners in buildings.

The amount of daily energy that could be saved is 14.44 million kWh, reaching 26.75% of the total electricity consumed by EVs, as shown in equations (12) and (13):

$$\Delta P_5 = P_5 \times N_2 \times k_2 = (5 \times 10^6) \times 24 \times 12.03\% = 14.44 \times 10^6 \,(\text{kWh}) \tag{12}$$

$$k_3 = \frac{\Delta P_5}{E_2 \times L \times N_1} = \frac{14.44 \times 10^6}{0.346 \times 30 \times (5.2 \times 10^6)} \times 100\% = 26.75\% \tag{13}$$

where ΔP_5 is the decreased energy consumed by air conditioners in buildings with CVs replaced, and k_3 is the ratio of ΔP_5 to energy consumed by EVs. With the decrease in air-conditioning energy consumption, less heat would be emitted, which would also contribute to mitigating UHIE and energy saving.

Reduction of CO₂. In 2012 in China, 740 g of CO_2 was emitted when 1 kWh of electricity was supplied to consumers[30]. Therefore, when 14.44 million kWh are saved, CO_2 emissions could be reduced 10,686 tonnes.

The data in this paper are mainly from the government of Beijing and the State Grid Beijing Electric Power Company. In this paper, we have to use some data of other years because some data of 2012 are not available. Therefore, our estimation of the benefits of replacing CVs with EVs is slightly lower than its actual contribution.

According to the analysis and estimation above, the replacement of CVs by EVs can substantially alleviate UHIE in the summer in metropolitan areas, which can improve the local climate, significantly reduce air-conditioning energy consumption and greenhouse gas emissions, thus helping to address global climate change.

1. Zentrum für Sonnenenergieund Wasserstoff-Forschung Baden-Württemberg (ZSW), *Weltweit über 400.000 Elektroautos unterwegs*. News (2014) Available at:

http://www.zsw-bw.de/infoportal/presseinformationen/presse-detail/weltweit-ueber-400000-elektroautos-unterwegs.html (Accessed: 31th March 2014) (in German).

2. Kintisch, E. Unclogging urban arteries. *Science* **319**, 750–751 (2008).
3. Zehner, O. Unclean at any speed. *IEEE Spectrum* **50**, 40–45 (2013).
4. Michalek, J. J. *et al.* Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits. *Proc Nat Acad Sci USA* **108**, 16554–16558 (2011).
5. Sanderson, K. *Why it's hot in the city. Nature News.* (2009) Available at: http://www.nature.com/news/2009/091224/full/news.2009.1164.html (Accessed: 24th December 2009).
6. China's Energy Information Network, *Beijing is in high temperature recently. News* (2010) Available at: http://epb.nengyuan.net/2010/0706/15047_6.html (Accessed: 6th July 2010) (in Chinese).
7. Mu, Y. *7000 traffic policemen stick to their post in the high temperature of 40.3°C. Sina news* (2010) Available at: http://auto.sina.com.cn/service/2010-07-06/1112621362.shtml (Accessed: 6th July 2010) (in Chinese).
8. Hashem, A. Energy saving potentials and air quality benefits of urban heat island mitigation. in *Proceedings of the first international conference on passive and low energy cooling for the built environment.* Athens: Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA Press (2005, May).
9. Grimm, N. B. *et al.* Global change and the ecology of cities. *Science* **319**, 756–760 (2008).
10. Kolokotroni, M., Giannitsaris, I. & Watkins, R. The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. *Solar Energy* **80**, 383–392 (2006).
11. Li, C. *et al.* Interaction between urban microclimate and electric air-conditioning energy consumption during high temperature season. *Applied Energy* **117**, 149–156 (2014).
12. Yang, J., Liu, Y., Qin, P. & Liu, A. A. A review of Beijing's vehicle lottery. *Environment for Development Discussion Paper Series* **1**, 1–30 (2014).
13. Hashem, A. *et al. Reducing Urban Heat Island: Compendium of Strategies, Urban Heat Island Basics. Technical report.* (2013) Available at: http://www.epa.gov/heatislands/resources/pdf/BasicsCompendium.pdf (Accessed: 29th August 2013).
14. Huo, H., Zhang, Q., Wang, M. Q., Streets, D. G. & He, K. Environmental implication of electric vehicles in China. *Environment Science Technology* **44**, 4856–4861 (2010).
15. Memon, R. A., Leung, D. Y. C. & Liu, C. H. An investigation of urban heat island intensity (UHII) as an indicator of urban heating. *Atmospheric Research* **94**, 491–500 (2009).
16. Li, Y. & Zhao, X. An empirical study of the impact of human activity on long-term temperature change in China: A perspective from energy consumption. *Journal of Geophysical Research* **17**, 1–12 (2012).
17. Yang, S. *Basis of Heat Transfer* [Yang, S. (ed.)] [442] (Higher Education Press, Beijing, 2003) (in Chinese).
18. China meteorological administration, *China Meteorological Yearbook 2013. Technical report.* (2013) Available at: http://lib.cnki.net/cyfd/J154-N2014090088.html (Accessed: December 2013) (in Chinese).
19. Chen, L., Zhu, W., Zhou, X. & Zhou, Z. Characteristics of the heat island effect in Shanghai and its possible mechanism. *Advances in Atmospheric Sciences* **20**, 991–1001 (2003).
20. Zhou, Y. & Savijärvi, H. The effect of aerosols on long wave radiation and global warming. *Atmospheric Research* **135–136**, 102–111 (2014).
21. Baumgardner, D. & Raga, G. Changes in precipitation intensity in Mexico City: Urban Heat island effect or the impact of aerosol pollution? (2014) Available at: http://www.researchgate.net/publication/237197120_CHANGES_IN_PRECIPITATION_INTENSITY_IN_MEXICO_CITY_URBAN_HEAT_ISLAND_EFFECT_OR_THE_IMPACT_OF_AEROSOL_POLLUTION (Accessed: 16th May 2014).
22. Alson, J. *et al. Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2013. Technical report.* (2014) Available at: http://www.epa.gov/heatislands/resources/pdf/BasicsCompendium.pdf (Accessed: 8th October 2014).
23. Hou, C., Wang, H. & Ouyang, M. Survey of daily vehicle travel distance and impact factors in Beijing. *in Proceedings of 7th IFAC Symposium on Advances in Automotive Control.* Tokyo: International Federation of Automatic Control Press (2013, September).
24. Beijing Municipal Bureau of Statistics, Beijing's Statistical Bulletin of National Economic and Social Development in 2012. *Technical report.* (2013) Available at: http://www.bjstats.gov.cn/xwgb/tjgb/ndgb/201302/t20130207_243837.htm (Accessed: 7th February 2013) (in Chinese).
25. Beijing Municipal Bureau of Statistics, *Beijing Statistical Yearbook 2012. Technical report.* (2012) Available at: http://www.bjstats.gov.cn/nj/main/2012-tjnj/index.htm (Accessed: September 2012) (in Chinese).
26. State Grid, *China Electric Power Yearbook 2013. Technical report.* (2013) Available at: http://wenku.baidu.com/link?url=P4lh2bUHuaaXuFZlZ-7Ia5R8cFF79oWyLHv-XyVQZrdjsz6-QfQgBDQ6P7NHZsj1GcDl8LlsVjFVr1yZhGFYR1klZi3HWf4-sxiiCQdZ7LW (Accessed: 1st December 2013) (in Chinese).
27. Lei, B. The high temperature increases the proportion of air conditioning load and the power grid companies response positively. *News* (2012) Available at: http://www.indaa.com.cn/dwxw2011/dwyw/201208/t20120827_1117010.html (Accessed: 27th August 2012) (in Chinese).
28. Liao, M. *The HII would be reduced more than ten percent in 15 years in Beijing. News* (2005) Available at: http://news.xinhuanet.com/newscenter/2005-08/23/content_3392449.htm (Accessed: 23th August 2005) (in Chinese).
29. Di, S., Wu, W., Liu, H., Yang, S. & Pan, X. The correlationship between urban greenness and heat island effect with RS technology: A case study within 5th Ring Road in Beijing. *Journal Geo-Information Science* **4**, 481–489 (2012). (in Chinese).
30. Birol, F. *et al. World Energy Outlook Special Report 2013: Redrawing the Energy-Climate Map. Technical report.* (2013) Available at: http://www.iea.org/publications/freepublications/publication/WEO_Special_Report_2013_Redrawing_the_Energy_Climate_Map.pdf (Accessed: 21th September 2014).

Author contributions

C.L. and J.L. designed the research; C.L., Y.C., M.Z., J.L. and H.S. performed the research; C.L., M.Z., J.L. and H.S. analysed the data; and C.L., J.L., Y.C., M.Z., J.W., H.S. and Y.G. wrote the paper. All authors reviewed the manuscript.

Additional information