

# Evaluation of the environmental impact of the urban energy lifecycle based on lifecycle assessment

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**Abstract** Energy resources have environmental impact through their entire lifecycle. The evaluation of the environmental impacts of the energy lifecycle can contribute to decision making regarding energy management. In this paper, the lifecycle assessment (LCA) method is introduced to calculate the environmental impact loads of different types of energy resources (including coal, oil, natural gas, and electricity) used in urban regions. The scope of LCA includes the production, transportation, and consumption processes. The pollutant emission inventory is listed, and the environmental impact loads are acquired through the calculation of environmental impact potentials, normalization, and weighted assessment. The evaluation method is applied to Beijing, China, revealing that photochemical oxidant formation and acidification are the primary impact factors in the lifecycle of all energy resources and that the total environmental impact load increased steadily from 132.69 million person equivalents (PE) in 1996 to 208.97 million PE in 2010. Among the energy types, coal contributes most to the environmental impact, while the impacts caused by oil, natural gas, and electricity have been growing. The evaluation of the environmental impact of the urban energy lifecycle is useful for regulating energy structures and reducing pollution, which could help achieve sustainable energetic and environmental development.

**Keywords** environmental impact, urban energy lifecycle, lifecycle assessment (LCA), Beijing

## 1 Introduction

Energy resources have driven social development (Su et

al., 2010; Ji, 2011; Dong et al., 2012). However, all energy sources affect the environment throughout their lifecycles, from production to transportation to consumption. Therefore, the evaluation of the impact of these energy sources is of great interest. Lifecycle assessment (LCA) is a common, useful methodology that can be applied to presenting the quantitative merits of different energy resources (Wackernagel and Yount, 1998; Manzini and Martínez, 1999; Jungbluth et al., 2005). Moreover, the evaluation of the environmental impact of different energy resources throughout their lifecycles helps to provide a comprehensive understanding of the environmental characteristics of energy systems and can be used to make well-informed, scientifically sound energy management decisions.

In recent years, many approaches have been applied to evaluate the environmental impact caused by pollutant emission in urban regions (Yan et al., 2009; Ji and Chen, 2010; Gasol et al., 2011; Guo et al., 2012; Wang et al., 2012; Wu et al., 2012), among which LCA is the most extensively used method. According to the Society of Environmental Toxicology and Chemistry's (SETAC) definition (Consoli, 1993), LCA is a methodology "to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements". Many studies on LCA have been carried out on one type of energy resource, such as electricity or natural gas. Odeh and Cockerill (2008) examined the lifecycle of greenhouse gas emissions from existing UK pulverized coal power plants. Kannan et al. (2007) performed LCA and lifecycle cost analyses for five centralized and distributed power generation technologies in Singapore. Shafie et al. (2012) conducted the lifecycle analysis of electricity derived from rice husk combustion in the rice mills. Sebastián et al. (2011) applied the LCA

method to compare the potential of greenhouse gas emission reduction between two alternatives of biomass electricity generation. Riva et al. (2006) applied LCA to evaluate the environmental advantages of natural gas over other fossil fuels.

Most LCA studies on energy resources focus on certain energy technologies and are limited to one type of energy resource. Few studies have been carried out on an urban scale to evaluate the environmental impact of all energy resources using LCA. A more comprehensive evaluation and comparison of the environmental impact of the lifecycle of various energy resources is required to devise reasonable strategies for urban energy use and the alleviation of energy-related environmental effects.

In this study, LCA is applied to evaluate the environmental impact of the lifecycle of four types of energy resources, coal, oil, natural gas, and electricity, in Beijing, China. The calculation method is introduced in the Methodology section. The remainder of the text presents the case study, results, discussion, and conclusions.

## 2 Methodology

Focusing on the four main energy sources (coal, oil, natural gas, and electricity), the application of LCA to assess the environmental impact of the urban energy lifecycle usually includes five steps: scope definition, inventory analysis, calculation of environmental impact potential, normalization, and weighted assessment.

(1) The scope of LCA includes all aspects of urban energy lifecycle: production, transportation, and consumption. Specifically, the coal lifecycle includes extraction, washing, transportation (including railway and highway), and consumption; the oil lifecycle includes extraction and refining, transportation (including railway, highway, and pipeline), and consumption; and the natural gas lifecycle includes extraction, pipeline transportation, and consumption. Because electricity transportation and consumption have little environmental impact, its lifecycle only includes electricity production, which can be subdivided into the processes of coal production, coal transportation, and electricity generation.

(2) Based on the scope definition, the emissions are determined for the full lifecycle of the energy resources, from production to transportation and consumption. Considering data availability, the pollutant emissions caused by energy production and consumption are calculated according to the emission coefficient per unit of energy resource using previous research results and acknowledged materials (Yuan et al., 2006). The pollutants emitted in the transportation process are related to the modes of transportation and travelling distance. In the case of Beijing, coal is primarily transported by rail from Shanxi and Inner Mongolia, oil is primarily transported by tankers

from Hebei, and natural gas is primarily transported by pipelines from Shaanxi (Riva et al., 2006). These differing transportation processes will in turn produce differing amounts of pollutants. The pollutants produced per unit of the studied energy resources are quantified in Table 1.

(3) According to the inventory analysis and an operational guide developed by Leiden University in the Netherlands (Guinée et al., 2001), the environmental impacts of global warming, acidification, eutrophication, photochemical oxidant formation, human toxicity potential, smoke and dust, and solid waste are selected in this study. The environmental impact potential of these seven types of impacts is calculated:

$$EP_{ij} = \sum_t EP_{ijt} = \sum_t (Q_{it} \times EF_{jt}), \quad (1)$$

where  $i$  is the energy resource type;  $j$  and  $t$  are the environmental impact type and the pollutant type, respectively;  $EP_{ij}$  is the  $j^{\text{th}}$  environmental impact potential per unit of energy resource  $i$ ;  $EP_{ijt}$  is the  $j^{\text{th}}$  environmental impact potential of pollutant  $t$ ;  $Q_{it}$  is the amount of pollutant  $t$  produced per unit of energy resources  $i$  ( $t/10^4$  tce); and  $EF_{jt}$  is the characterization factor for the  $j^{\text{th}}$  environmental impact potential of pollutant  $t$ , as shown in Table 2.

(4) The environmental impact potential is then normalized to allow comparison. It is expressed in person equivalents (PE), which represents the annual average potential impact on one person. The normalized results are calculated according to the normalization factors listed in the fifth column of Table 2.

$$NP_{ij} = \frac{EP_{ij}}{R_j}, \quad (2)$$

where  $NP_{ij}$  is the  $j^{\text{th}}$  normalized environmental impact potential (PE) and  $R_j$  is the normalization factor of the  $j^{\text{th}}$  environmental impact (impact potential unit  $\cdot$  person $^{-1}$   $\cdot$  year $^{-1}$ ). We select per capita environmental impact potentials in 1990 as the normalization reference.

(5) To compare different types of environmental impacts, we sort the seven environmental impacts based on importance and assigned weights according to the LCA model built by Yang et al. (2002), as shown in the sixth column of Table 2. Combining the normalization results with the weights of each type of impact, the final environmental impact loads of coal, oil and natural gas are obtained, as indicated in Table 3.

$$EIL_i = \sum_j (WF_j \times NP_{ij}), \quad (3)$$

where  $EIL_i$  is the environmental impact load and  $WF_j$  is the weight of the  $j^{\text{th}}$  environmental impact, as shown in the sixth column of Table 2.

**Table 1** Pollutants produced per unit of energy ( $t/10^4$  tce)

| Energy resource | Pollutant type                | Production | Transportation | Consumption | Total    |
|-----------------|-------------------------------|------------|----------------|-------------|----------|
| Coal            | CO <sub>2</sub>               | 8.47E+01   | 3.09E+03       | 2.74E+04    | 3.06E+04 |
|                 | CO                            | 7.07E-02   | 9.44E-01       | 1.86E+01    | 1.96E+01 |
|                 | SO <sub>2</sub>               | 1.02E-01   | 2.39E+00       | 2.80E+02    | 2.82E+02 |
|                 | NO <sub>x</sub>               | 5.87E-01   | 7.29E-01       | 1.24E+02    | 1.26E+02 |
|                 | C <sub>n</sub> H <sub>m</sub> | 1.28E+02   | 8.96E-02       | 6.16E+00    | 1.34E+02 |
|                 | Smoke                         | 1.24E+01   | 3.00E+02       | 1.31E+02    | 4.44E+02 |
|                 | Solid waste                   | 6.73E+02   | –              | 1.32E+03    | 1.99E+03 |
| Oil             | CO <sub>2</sub>               | 5.46E+02   | 4.73E+02       | 2.14E+04    | 2.24E+04 |
|                 | CO                            | 5.28E-02   | 4.98E+00       | 1.62E+00    | 6.65E+00 |
|                 | SO <sub>2</sub>               | 1.40E+00   | 3.61E-01       | 5.83E+01    | 6.01E+01 |
|                 | NO <sub>x</sub>               | 1.36E+00   | 1.52E+00       | 1.17E+02    | 1.20E+02 |
|                 | C <sub>n</sub> H <sub>m</sub> | 5.34E-02   | 6.80E-01       | 1.62E+00    | 2.35E+00 |
|                 | Smoke                         | 6.70E-01   | –              | 1.05E+01    | 1.12E+01 |
|                 | Solid waste                   | 4.19E+01   | –              | –           | 4.19E+01 |
| Natural gas     | CO <sub>2</sub>               | 5.62E+02   | 2.92E-01       | 1.63E+04    | 1.68E+04 |
|                 | CO                            | 5.44E-02   | –              | 2.05E+00    | 2.10E+00 |
|                 | SO <sub>2</sub>               | 1.44E+00   | 4.21E-04       | 7.22E-02    | 6.17E+00 |
|                 | NO <sub>x</sub>               | 1.41E+00   | 1.72E-02       | 1.39E+01    | 1.53E+01 |
|                 | C <sub>n</sub> H <sub>m</sub> | 5.50E-02   | 1.35E-01       | 3.61E-01    | 5.51E-01 |
|                 | Smoke                         | 6.90E-01   | –              | 2.10E+00    | 2.79E+00 |
|                 | Solid waste                   | 4.33E+01   | –              | –           | 4.33E+01 |
| Electricity     | CO <sub>2</sub>               | 3.65E+04   | –              | –           | 3.65E+04 |
|                 | CO                            | 3.57E+00   | –              | –           | 3.57E+00 |
|                 | SO <sub>2</sub>               | 2.72E+02   | –              | –           | 2.72E+02 |
|                 | NO <sub>x</sub>               | 2.47E+02   | –              | –           | 2.47E+02 |
|                 | C <sub>n</sub> H <sub>m</sub> | 1.43E+02   | –              | –           | 1.43E+02 |
|                 | Smoke                         | 1.25E+02   | –              | –           | 1.25E+02 |
|                 | Solid waste                   | 7.47E+02   | –              | –           | 7.47E+02 |

### 3 Case study

#### 3.1 Study area

Beijing, the capital of China, is located in the northern part of the North China Plain. Due to rapid socio-economic development, energy use in Beijing increased from 1996–2010. The amount of total energy use in 2010 was 69.54 million tce, compared to 37.35 million tce in 1996 (Beijing Municipal Bureau of Statistics, 2011). The main energy resources in Beijing for end-use consumption include coal, oil, natural gas and electricity, accounting for over 96% of the total energy consumption. The majority of the energy supply, including more than 90% of coal, all crude oil, all natural gas, and approximately 51%–70% of electricity, is imported from other regions. The concrete consumption structure of the four energy resources during 1996–2010 is

shown in Fig. 1. As shown, coal has historically accounted for a significant part of Beijing's energy consumption, but its relative use is decreasing slowly. The other types of energy resources have continued to rise in popularity in recent years.

#### 3.2 Results and discussion

##### 3.2.1 Environmental impact categories of different energy types

The relative contributions of the different types of environmental impact vary by energy resource (Fig. 2). Generally speaking, photochemical oxidant formation and acidification are the main impacts caused by the studied energy resources.

In terms of coal, smoke and dust as well as

**Table 2** Environmental impact potential of the studied energy resources

| Impact category                 | Pollutant parameter           | Characterization factor <sup>a)</sup> | Impact potential unit                | Normalization factor <sup>a)</sup><br>(impact potential unit<br>·person <sup>-1</sup> ·year <sup>-1</sup> ) | Weight   |
|---------------------------------|-------------------------------|---------------------------------------|--------------------------------------|---|----------|
| Global warming                  | CO <sub>2</sub>               | 1                                     | tCO <sub>2</sub> eq./t               | 8.70E+00  | 8.30E-01 |
|                                 | CO                            | 2                                     |                                      |   |          |
|                                 | NO <sub>x</sub>               | 320                                   |                                      |   |          |
|                                 | C <sub>n</sub> H <sub>m</sub> | 3                                     |                                      |   |          |
| Acidification                   | NO <sub>x</sub>               | 0.7                                   | tSO <sub>2</sub> eq./t               | 3.50E-02  | 7.30E-01 |
|                                 | SO <sub>2</sub>               | 1                                     |                                      |   |          |
| Eutrophication                  | NO <sub>x</sub>               | 1.35                                  | tNO <sub>3</sub> <sup>-</sup> eq./t  | 5.90E-02  | 7.30E-01 |
| Photochemical oxidant formation | CO                            | 0.03                                  | tC <sub>2</sub> H <sub>2</sub> eq./t | 7.60E-04  | 5.30E-01 |
|                                 | NO <sub>x</sub>               | 0.03                                  |                                      |   |          |
|                                 | SO <sub>2</sub>               | 0.05                                  |                                      |   |          |
|                                 | CH <sub>4</sub>               | 0.01                                  |                                      |   |          |
| Human toxicity potential        | CO                            | 0.01                                  | t body mass/t                        | 1.09E-01  | 2.98E-01 |
|                                 | NO <sub>x</sub>               | 0.78                                  |                                      |   |          |
|                                 | SO <sub>2</sub>               | 1.2                                   |                                      |   |          |
| Smoke and dust                  | Smoke                         | 1                                     | t PM <sub>10</sub> eq./t             | 1.80E-02  | 6.10E-01 |
| Solid waste                     | Solid waste                   | 1                                     | t waste                              | 2.51E-01  | 6.20E-01 |

a) Data source: Yang et al., 2002.

**Table 3** Environmental impact load of the studied energy resources

| Impact category                 | Environmental impact load (PE) |          |             |             |
|---------------------------------|--------------------------------|----------|-------------|-------------|
|                                 | Coal                           | Oil      | Natural gas | Electricity |
| Global warming                  | 6.79E+03                       | 5.80E+03 | 2.07E+03    | 1.11E+04    |
| Acidification                   | 7.72E+03                       | 3.01E+03 | 2.55E+02    | 9.28E+03    |
| Eutrophication                  | 2.10E+03                       | 2.01E+03 | 2.55E+02    | 4.12E+03    |
| Photochemical oxidant formation | 1.34E+04                       | 4.74E+03 | 4.14E+02    | 1.53E+04    |
| Human toxicity potential        | 1.19E+03                       | 4.53E+02 | 3.76E+01    | 1.42E+03    |
| Smoke and dust                  | 1.50E+04                       | 3.79E+02 | 9.46E+01    | 4.25E+03    |
| Solid waste                     | 4.92E+03                       | 1.03E+02 | 1.07E+02    | 1.85E+03    |
| Total                           | 5.12E+04                       | 1.65E+04 | 3.24E+03    | 4.73E+04    |

photochemical oxidant formation are the main contributors to environmental impact, accounting for 29.38% and 26.19%, respectively. Notably, the processes of transportation and consumption release large amounts of smoke. Acidic gasses, such as SO<sub>2</sub> and NO<sub>x</sub>, are produced by coal consumption, which lead to acidification and are also the main contributors to photochemical oxidant formation.

Global warming is the primary impact caused by oil and natural gas (35.19% and 64.05%, respectively), followed by photochemical oxidant formation and acidification. The main greenhouse gasses, CO<sub>2</sub> and NO<sub>x</sub>, are the most dangerous of the gaseous pollutants caused by oil and natural gas consumption. NO<sub>x</sub> is still the main contributor to photochemical oxidant formation and acidification.

Regarding electricity, photochemical oxidant formation is the primary type of impact, accounting for 32.38%, followed by global warming and acidification. Coal-fired power generation produces large amounts of SO<sub>2</sub>, NO<sub>x</sub>, and hydrocarbons, which are the main photochemical gasses and acidic gas.

### 3.2.2 Total environmental impact load of energy resources

The total environmental impact load of the energy lifecycle for Beijing increased steadily from 132.69 million PE in 1996 to 208.97 million in 2010, with an annual average increase of 6.66 million (Fig. 3). Among the four types of energy resources, coal is the main contributor to the

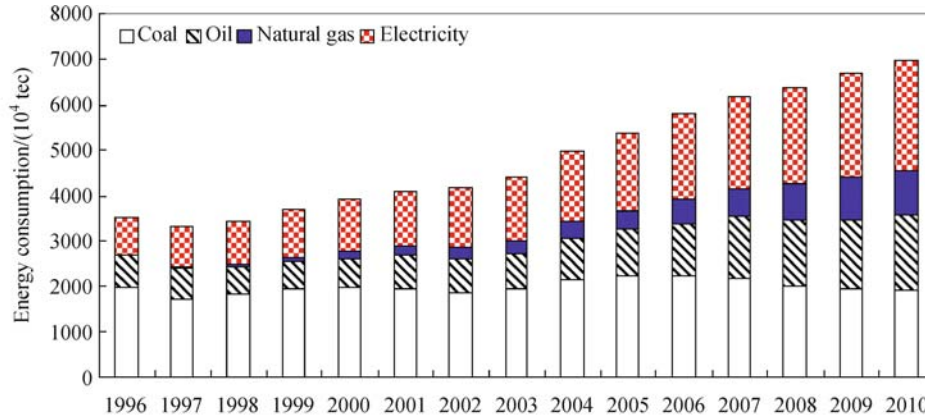


Fig. 1 Consumption of four energy resources in Beijing during 1996–2010.

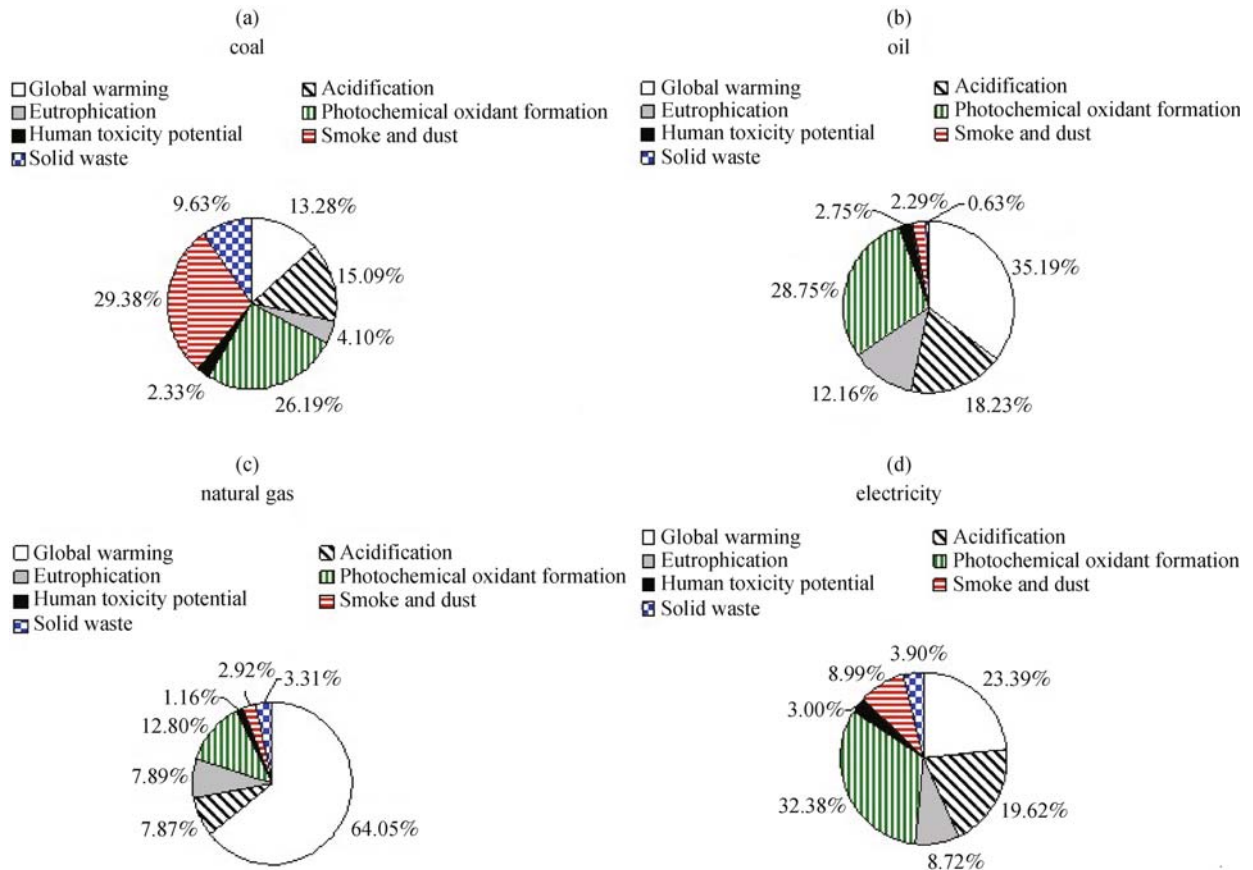


Fig. 2 Relative proportions of the environmental impacts of the four studied energy resources.

environmental impact, especially from 1996 to 2005, when it accounted for over 60% of the total impact load. However, the coal-related impact load has decreased every year since 2005 as a result of continuously decreasing coal consumption. Compared with coal, the impact load of oil, natural gas and electricity increased during 1996–2010. The impact load of oil increased relatively slowly, by 58.18% from 1996 to 2010. The environmental impacts

caused by natural gas were minor because it consumed low levels of energy and emitted few pollutants. However, the impact load has grown by 98.07% from 1996 to 2010 because of the high increase in the use of natural gas in Beijing. Electricity is another main contributor to the environmental impact. With the significant growth of electricity consumption, the impact load of electricity increased by 74.84% from 1996 to 2010. Its contribution to

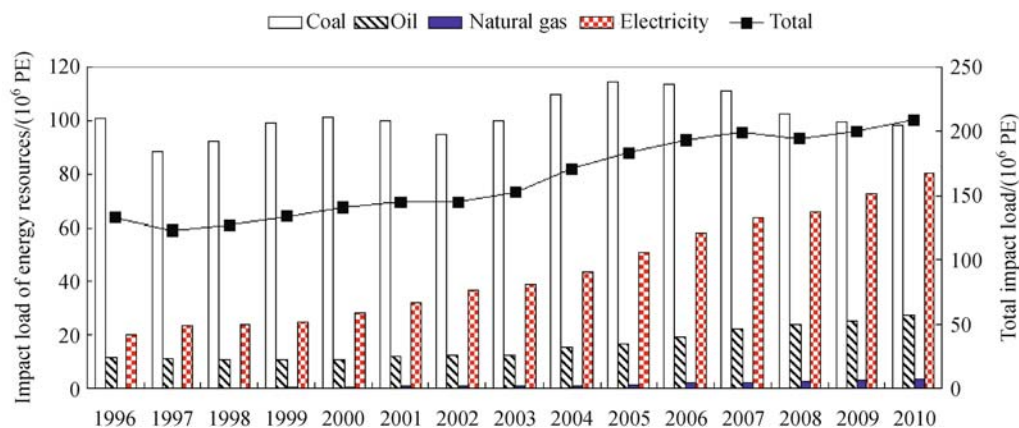


Fig. 3 Environmental impact loads of energy resources in Beijing.

the total environmental impact was over 30% from 2006 to the end of the study. It is estimated that electricity contributed most to the growth of the total environmental impacts.

In terms of the concrete impact types, photochemical oxidant formation remained the top contributor, accounting for 27.34%–28.69% during 1996–2010. The contribution of smoke and dust, which also had a substantial contribution, gradually declined from 23.96% in 1996 to 17.64% in 2010 because of the decline of coal use in Beijing. Moreover, global warming and acidification also have large impacts (Fig. 4).

### 3.2.3 Suggestions and potential future development

To reduce the environmental impact of the urban energy lifecycle, measures should be implemented to optimize the energy structure and reduce pollutant emission in the energy lifecycle. According to the “Twelfth Five-Year

Plan” in Beijing, the government will strongly encourage the utilization of natural gas and the input of electricity while further reducing coal consumption. Natural-gas-fired electricity generation capacities will be expanded, and renewable energy can be encouraged to improve the energy structure and reduce environmental pollution. In addition to energy structure optimization, environmental pollution should be reduced during the processes of energy production, transportation, and consumption. Possible approaches include reducing the emission and comprehensive use of gas in the process of coal extraction, backfilling coal gangue underground to reduce solid waste, applying dust suppressant to reduce dust in the transportation process, improving coal-combustion boilers to increase efficiency, and adopting advanced desulfurization and denitrification techniques in energy industries.

In future work, more processes in the lifecycle, such as plant construction, can be taken into account when evaluating the environmental impact. The definition of

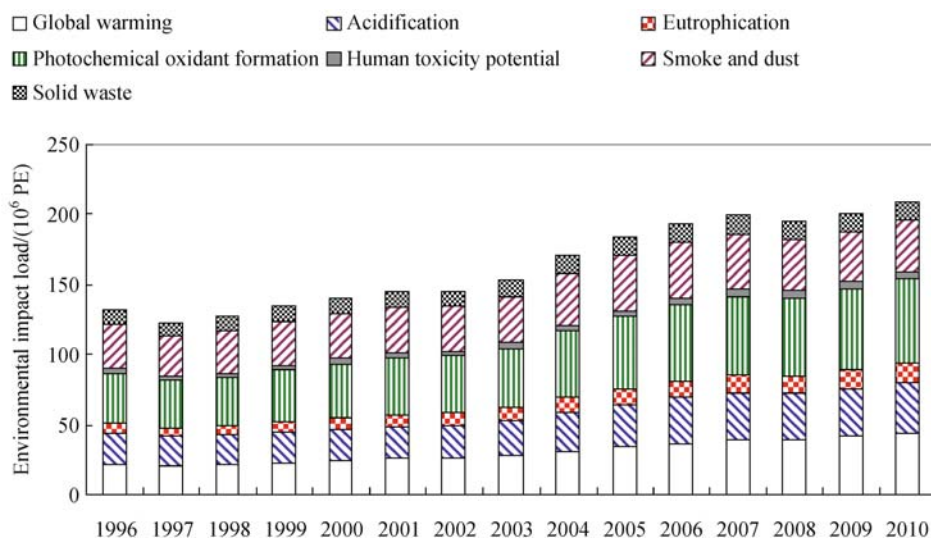


Fig. 4 Environmental impact loads of the seven impact types in Beijing.

parameters in the LCA (e.g., characterization and normalization factors, weights) should be regulated scientifically to reduce uncertainty. In addition, reliable, complete data for emission inventories in the urban energy lifecycle are greatly needed for the evaluation of environmental impact.

## 4 Conclusions

Energy plays a significant role in urban development. However, the pollutants produced in the energy lifecycle have strong environmental impacts. Evaluating the environmental impact of the lifecycle of all energy resources on an urban scale will help decision makers propose and debate comprehensive plans for managing energy systems.

In this paper, LCA is introduced to evaluate the environmental impact of energy lifecycle at urban scale. The scope of LCA includes all aspects of the energy lifecycle covering production, transportation, and consumption, and the pollutant emissions due to multiple energy sources, including coal, oil, natural gas, and electricity, are all presented in the inventory. Seven kinds of environmental impacts are considered, including global warming, acidification, eutrophication, photochemical oxidant formation, human toxicity potential, smoke and dust, and solid waste. The results of Beijing show that photochemical oxidant formation and acidification are the main impact types caused in the lifecycle of all energy resources. The total environmental impact load throughout the energy lifecycle in Beijing increased steadily during the study period. Additionally, coal was found to always be the biggest contributor to the environmental impacts although its related impact decreased during 2005–2010. The impact load of oil, natural gas, and electricity increased during the study period while electricity contributed most to the growth of the total environmental impacts.

Correspondingly, energy structure should be optimized to reduce the pollutant emission and related environmental impact in the urban energy lifecycle. The consumption of coal, which is the biggest contributor to the environmental impacts, must be restricted in the future. The consumption of electricity, which is the second largest contributor to, and most responsible for growth of environmental impacts, should be cautiously controlled. The utilization of natural gas can be encouraged. Furthermore, other measures are also necessary to reduce the pollutant emission and related environmental impacts in the whole urban energy lifecycle such as improvement of technique and technology, recycling of waste, and exploitation of renewable energy.

LCA can be applied to evaluate environmental impact of the urban energy lifecycle. It can contribute to efficient energy planning and utilization, the reduction of environmental pollution, and the implementation of sustainable energetic and environmental development.

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