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Extended exergy based ecological accounting for the transportation sector in China

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ABSTRACT

Extended exergy appears to be the only currently available second-law based and unified metric for ecological accounting, and it represents an effective measure of the technical, social and environmental impacts associated with the general "operation" of a complex society. The method of analysis is called Extended Exergy Accounting (EEA), and it was used in this study to assess the primary resource-based ecological cost of material and energy resources, human labor, capital contributions, and environmental impact of the transportation system in China on a 2008 database. Sub-sector distribution analyses are presented for the extended exergy cost by considering four modes of transportation (highways-i.c.e. powered, railways, waterways and civil aviation). A chemical exergy accounting of the cumulatively emitted CO, NOx and SO_2 was applied as a preliminary step required by EEA to assess the overall ecological impact of waste gas emissions by calculating an "exergetic avoidance cost". The results showed that natural input represents the largest portion of the extended exergy depletion in transportation sector (TR-sector), and highways require the highest extended exergy investment among the considered modes. In the conclusions, a few pertinent recommendations based on our results are put forth, to increase the understanding of technical-social-ecological energy depletion, to promote the operational efficiency in transport system, and to indicate the limits of current waste gas emission reduction measures, thus providing a holistic method and a systematic view and thus help decision makers to devise policies for a less unsustainable development and for a more rational environmental management.

Contents

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) 2007 report, climate change has become an issue of global

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concern, and global warming is an important problem affecting not only human development but the very survival of the human race [1]. This warming is directly linked to the increase in the atmospheric concentration of greenhouse gases (GHG). Waste gas emission mitigation, which is directly related both to fossil energy consumption and to GHG production, is an issue involving the natural environment, the economic system and the policymaking sectors. Since the problem is acutely felt at international level, many countries all over the world have taken effectively pro-active measures, such as the "industrial energy tax", carbon emission trading, enhanced management and control over different sectors etc., aimed at meeting this challenge [2].

The transportation sector (TR) obtains almost 100% of its energy needs from fossil sources, and as such it is one of the major contributors both to energy final use and to GHG emissions. Specifically, the TR, being tightly interrelated with industrial and social development and with the definition of life standards, is responsible for an ever increasing environmental impact: urban air pollution and global warming result from both direct emissions (public and private vehicles, commercial trucks, cars and planes) and indirect emissions (development of traffic infrastructures). Thus, many countries have begun to closely monitor this important sector. The UK government passed a legislation called "Low Carbon Transportation Strategy" in 2009, and proactively took steps to encourage the voluntary adoption of emission reduction measures, set a goal of reduce 14% of carbon emission in traffic sector, and established a transparent monitoring and reporting system; some car manufacturers have signed a voluntary agreement with the European Union (EU) to cut carbon dioxide emissions from new passenger cars to 140 g/km by 2008; transport patterns are being transformed in many countries to encourage walking, cycling and a more systematic use of public transportation. For China, it has been calculated that 7.5% of the total final energy was used in the TR-sector in 2008 [3]. To a certain degree, car ownership pro capite is presently low compared with that of the developed countries; however, there is a great growth potential on car expenditure in the near future, and hence a correspondingly high potential for critical environmental impact derived from waste gas emission. The Chinese government has recognized the severity of traffic environmental impacts in recent years, and started to pursue steps toward a "greener" transportation system.

In order to formulate appropriate strategies and provide both theory-and-practice based evaluations on reducing environmental impacts, it is necessary to acquire an accurate quantitative assessment of the various waste gases emitted from the TR-sector. A series of researches have been done to gain a more significant understanding of the energy efficiency of the sector and of its environmental impact. In general, the world's transportation system is considered to be unsustainable because automobile use and density has strongly increased during the last few decades [4]. However, Richardson [5] suggested to turn down this statement, and considered that transportation systems enable a large number of people to access and exploit economic and social opportunities necessary for life maintaining. An assessment of energy utilization and waste gas emission in the TR-sector can be conducted along two main lines of thought: first, a quantitative estimation of energy depletion and environmental emission [6] can be sought after on the basis of energy, emergy and/or exergy efficiency indicators [7,8]. This kind of approach leads to a prescription about macroscopical energy and exergy flow diagrams or about a "desirable" life cycle process [9,10]: several applications to different countries, areas or social units have been published [7,11–17]. The second line of thought concentrates on the comprehensive impact of social, economical, ecological and political aspects within a sustainable perspective [18,19]: statistical analysis of specific vehicular functions and emissions are related to social development [20], GDP [21], global commercial activity [22], quality of public life [23], environmental emissions [24], strategies and solutions [25] and so on.

For a more precise and profound recognition of transportation's effects on human society, including ecological and sociological perspective and maintaining an intrinsic physical quality, the concept of exergy paves the way towards the development of a reasonably accurate method to estimate the effects of waste emission [8,9,26]. Recall that exergy is defined as the maximum work performed by a system in the process of reaching equilibrium with its reference environment [27–29], and thus constitutes a "thermodynamic measure" of the distance of the state of the system from that of the environment. When evaluating ecological cost, exergy can be regarded as a quantifier combining the quality and quantity of resource consumption and waste emission [30] with a conceptually correct foundation on the second law of thermodynamics. Closely related to use value, exergy analysis, which is a central concept of macroeconomics, has been combined with economics to quantify the cost of the exergy destruction and losses and the cost of artificial activities, thus optimizing various anthropic processes and improving the thermal-economic performances at each stage, thus facilitating downstream decision-making procedure [31–33]. A few applications also dealt with environmental discharges, and demonstrated the potential of exergy analysis as a tool for energy policy making [34,35].

Exergy analysis indeed offers a deep and broad insight into the structure of physical, thermodynamic and ecological costs. However, in view of the intrinsic social expense and "payback" for the sector's operation, which includes a series of activities connecting businesses, accelerating social development and ameliorating life standards, we need a more extensive and inclusive metric. Extended exergy enters the picture here: extended exergy accounting (EEA in the following of this paper), proposed by one of the authors [36,37], is an extension of traditional exergy analysis that expresses the primary production factors, (Labour and Capital, Materials and Energy) in units of "prime resource exergy equivalent", i.e., in kilojoules of primary exergy, and adds another factor, the Environmental Remediation Cost, also expressed in similar units: thus EEA may be regarded as an attempt to bridge the gap about the "production of value" that separates the majority of economists and energists [38,39].

EEA is a socio-economic construct with biophysical references, intended to balance the labor theory of value and the current thermodynamic theory: its quantifier, the extended exergy "cost", can be used as a goal function to optimize the allocation of the involved "values" (short for "use value" in this paper). Since primary resources, and in particular their exergy, are both the "fuel" for societal development and a "limit" for the carrying capacity of the Earth, EEA can be considered as a proper tool to measure the (exergy) cost of measures aimed at decreasing our degree of unsustainability: it does so not only by displaying the loss of available energy, but also supplying input conditions and allocations, for "more sustainable" solutions may in some cases require greater resource consumption than "less sustainable" ones [40]. Furthermore, new light is shed by EEA on the so-called "environmental externalities" problem, in that this theory augments the "cost" of the internal irreversibility of a system by charging its products with the remediation cost of its waste emissions.

This study presents an extended exergy analysis of the TR-sector in China to investigate the status of materials and energy use, social and economical input, and the environmental impact of waste gas discharge. Historically a bottleneck in the economic and social development of China, the transportation situation has been greatly improved in the last decade. By the end of 2008, the total highways length open to traffic had reached to 3.86 million km, of which expressway amounted to 65,000 km. The length of railways