Energy Economics 44 (2014) 448–455

Contents lists available at ScienceDirect

Energy Economics

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

Mitigating climate change: Decomposing the relative roles of energy conservation, technological change, and structural shift

Gouri Shankar Mishra *, Saleh Zakerinia, Sonia Yeh, Jacob Teter, Geoff Morrison

Institute of Transportation Studies, University of California, Davis, 1605 Tilia Street, Suite 100, Davis, CA 95616, United States

ARTICLE INFO

Article history:
Received 15 February 2013
Received in revised form 6 September 2013
Accepted 28 April 2014
Available online 16 May 2014

JEL classification:
C6 — Mathematical Methods and Programming
N7 — Transport, International and Domestic Trade, Energy, and Other Services
Q2 — Renewable Resources and Conservation, Environmental Management
Q3 — Nonrenewable Resources and Conservation
Q4 — Energy

Keywords:
Decomposition analysis
Integrated assessment model
Logarithmic Mean Weight Divisia Method (LDM)
Energy efficiency
Energy services
Greenhouse gas emissions
Transportation
Carbon capture and sequestration (CCS)
Primary energy
Useful energy

ABSTRACT

We decompose the contribution of five drivers of energy use and CO_2 emissions reductions in achieving climate change goals over 2005–2100 for various climate policy scenarios. This study contributes to the decomposition literature in three ways. First, it disaggregates drivers of energy demand into technological progress and demand for energy services, represented in terms of useful energy, allowing us to estimate their contributions independently — an improvement over other economy-wide decomposition studies. Secondly, this approach reduces the ambiguity present in many previous measures of structural change. We delineate structural shifts into two separate measures: changes in fuel mix *within* a given resource or service pathway; and changes in mix *among* distinct energy resources or end-use services. Finally, this study applies decomposition methods to energy and emission trajectories from two mutually informing perspectives: (i) *primary energy resources* — crude oil, natural gas, coal, nuclear, and renewables; and (ii) *end-uses of energy services* — residential and commercial buildings, industry, and transportation. Our results show that technological improvements and energy conservation are important in meeting climate goals in the first half of the coming century; and that nuclear and renewable energy and CCS technology are crucial in meeting more stringent goals in the second half of the century. We examine the relative roles of the drivers in reducing CO_2 emissions separately for developed and developing regions. Although the majority of energy and emission growth – and by extension the greatest opportunities for mitigation – will occur in developing countries, the decomposition shows that the relative roles of the five drivers are broadly consistent between these two regions.

1. Introduction

Prominent studies detailing measures needed to mitigate climate change (Fisher et al., 2007; Pacala and Socolow, 2004) and achieve energy security and independence (IEA, 2012) highlight the complementary roles of energy conservation, improvements in energy efficiency, substitution of fossil resources by renewables and high carbon with low carbon fossil resources, and carbon capture and sequestration (CCS). A number of studies have analyzed the historical evolution of energy use and CO_2 emissions to estimate the relative roles of these mitigation options on a global as well as regional scale (Lee and Oh, 2006; Zhang et al., 2009) and within and among specific end-use sectors (Schipper et al., 2011). Still others have undertaken cross-sectional analysis to compare differences in the relative roles of these drivers across regions (Lee and Oh, 2006; Schipper et al., 2001; Zhang and Ang, 2001).

A number of different metrics are used in decomposition analyses to characterize the relationship between energy demand and CO_2 emissions. Energy demand may be measured by *end-use service* per capita in physical terms — for example in ton-km (Kamakaté and Schipper, 2009) or passenger-km traveled (Schipper et al., 2011); by per capita *final energy consumption*; or "proxied" by sector-specific or economy-wide GDP as a measure of value-added (Zhang and Ang, 2001); or by

Abbreviations: ACP, aggressive climate policy; CCS, carbon capture and storage; IAM, integrated assessment model; IEA, International Energy Agency; LDV, light-duty vehicle; MCP, Moderate Climate Policy; NG, natural gas; N&R, nuclear and renewables; UE, useful energy.

* Corresponding author. Tel.: +1 510 224 3187.
E-mail addresses: gsmishra@ucdavis.edu (G.S. Mishra), mzakerinia@ucdavis.edu (S. Zakerinia), slyeh@ucdavis.edu (S. Yeh), jeteter@ucdavis.edu (J. Teter), gmorrison@ucdavis.edu (G. Morrison).

http://dx.doi.org/10.1016/j.eneco.2014.04.024
0140-9883/

total population (e.g. residential sector (IEA, 2004)). Similarly, there are differences in how decomposition analyses measure technological progress, which may be represented by changes in energy intensity (the reciprocal of energy efficiency). This is usually represented in units of final energy (fuel) input per dollar value-added. However, changes in this metric of energy intensity result from three factors: technological efficiency improvements, changes in per capita demand for energy services, and structural changes in the economy. For example, the transition from a predominately industrial to a service-oriented economy (a structural shift) could lead to a reduction in energy intensity as measured by final energy per unit GDP even in the absence of any technological progress or energy conservation (IEA, 2004). As a result of using a single mitigation driver to represent three separate factors (Fisher et al., 2007; Hanaoka et al., 2009), the *energy intensity* metric may distort conclusions about what is driving emission reductions.

The role of “structural change” in increasing or decreasing emissions is ambiguous, and depends both on the scope of analysis (single sector or economy-wide) and the definition of structural changes. For example, Lee and Oh (2006) conclude that the fuel switching (also called inter-fuel substitution) from high-carbon to low-carbon fuels dampened increases in CO_2 emissions in Asia Pacific Economic Cooperation countries between 1980 and 1998. The IEA (2004) analyzed emission growth in eleven IEA member countries from 1973 to 1998 and found that the changing fuel mix to end-use sectors (manufacturing, households, service, travel and freight) and shifts in the resource mix to the utility sector dampened CO_2 emissions. On the other hand, many sector-specific studies, in which structural changes are defined in terms of shares of end-use services being consumed, conclude that structural changes contribute to increase in emissions. Examples include Eom et al. (2012) analysis of the freight transportation in various countries, and Schipper et al. (2011) analysis of the U.S. freight and passenger transportation — where increasing shares of freight trucks over railroads and private LDVs over public modes contributed to rising CO_2 emissions. Similarly, the IEA (2004) found that larger houses increased the share of space heating relative to other residential energy requirements, and contributed to a rise in CO_2 emissions from the residential sector in 11 IEA countries. This highlights the need for a more comprehensive and refined definition of “structural change,” including decomposing changes in energy use and emissions from both changes in energy mix and end-use services.

This study contributes to the decomposition literature in three specific ways. First, as detailed in the Methodology section to follow, it improves upon previous decomposition methods adopted by studies forecasting economy-wide energy and emissions by further disaggregating drivers of energy demand into technological progress and demand for energy services, allowing us to estimate their contributions independently. Secondly, we delineate structural shifts into two separate measures: changes in fuel mix within a given resource or within a given service; and changes in mix of energy resources or end-use services. This approach resolves the ambiguity of the definition of structural change used in the past. Lastly, this study applies a decomposition of GHG abatement from two mutually informing perspectives: (i) *primary energy resources* — crude oil, natural gas (NG), coal, nuclear, and renewables (N&R); and (ii) *end-uses of energy services* — residential and commercial buildings, industry and transportation. We show that this dual approach leads to new and informative insights as to the drivers of energy use and carbon emissions across various technology assumptions and carbon policy scenarios. Finally, we examine the relative roles of the drivers in reducing CO_2 emissions separately for developed and developing regions.

This report is organized as follows. We describe our methodology in Section 2 and present the results in Section 3. We discuss the implications of the study and identify areas of further research in Section 4.

2. Methodology

2.1. Decomposition analysis

Following Zhang and Ang (2001) and Ang (2004), CO_2 emissions from energy use from a region in any given year may be represented by the following Kaya relationship:

$$C = \sum_j \sum_i \left(C_{i,j}/P_{i,j}\right)\left(P_{i,j}/U_{i,j}\right)\left(U_{i,j}/U_j\right)\left(U_j/U_{total}\right)\left(U_{total}/Pop\right) \quad (1)$$

where *C* is the total CO_2 emissions in billion tonnes (in a given region for a given year, symbols omitted for clarity), *P* and *U* are primary and useful energy in exajoules (EJ), respectively, and *Pop* is the population. Useful energy (UE) is defined later in this section. We analyze changes in CO_2 emissions from the *energy resource perspective* and the *end-user service perspective*. For analysis from the energy resource perspective, subscript *j* refers to an energy resource in our analysis; this stands for one of four resource classes: (i) crude oil, (ii) natural gas (NG), (iii) coal, and (iv) nuclear & renewables (N&R). Subscript *i* refers to energy pathways derived from a given energy resource *j*. An example of an energy pathway from resource *j* where *j* is natural gas is NG → electricity → hydrogen (H_2) → transportation. For analysis from the end-user perspective, *j* refers to one of three end-use sectors: (i) buildings (both commercial and residential), (ii) industry, and (iii) transportation; while *i* refers to all pathways within *j* that provide the same energy service. For example, coal → electricity → transportation and NG → electricity → transportation are two competing pathways (*i*) providing transportation services (*j*).

Eq. (1) may be rewritten as a series of indicators as shown in Eq. (2).

$$C = \sum_j \sum_i \left(CI_{i,j}\right)\left(I_{i,j}\right)\left(FM_{i,j}\right)\left(S_j\right)(D)(Pop). \quad (2)$$

$CI_{i,j}$ and $I_{i,j}$ refer to *carbon intensity* (gram CO_2/MJ primary energy) and *lifecycle energy intensity* (MJ *primary* energy *in*/MJ *UE out*) of an energy pathway *i,j* (Nakićenović et al., 1996; Yeh et al., 2013).

The terms $FM_{i,j}$ and S_j have slightly different interpretations depending upon whether decomposition is conducted from the perspective of energy resources or end-use services. In the former, $FM_{i,j}$ refers to the share of an energy pathway *i* derived from the given energy resource *j*; we call this the *fuel mix* within a given resource. S_j refers to the share of UE derived from energy resource *j* relative to the total UE consumed in the economy; we call this the *energy resource mix*. Take the example of $FM_{coal \rightarrow electricity \rightarrow cars,\ coal}$ and S_{coal}. The former refers to the fraction of total UE derived from coal (primary energy resource) used for electric passenger cars; while the latter refers to share of coal-derived UE in total UE consumed in any region in a given year.

In decomposition analysis from the end-use perspective, $FM_{i,j}$ refers to the share of an energy pathway *i* used to provide energy service for the given end-use *j* (fuel pathway mix). S_j refers to the share of UE consumed in a given end-use sector *j* to the total UE consumed in the economy (end-use services mix). Thus $FM_{coal \rightarrow electricity \rightarrow cars,\ transport}$ refers to the share of total UE consumed for transportation purposes that is derived from coal-fired electricity and used for passenger car mobility. $S_{transport}$ is the share of all transportation based UE ($FM_{coal \rightarrow electricity \rightarrow cars,\ transport}$ being one example) in total UE consumed in any region in a given year.

D is the UE demand (MJ), a concept with numerous definitions. Lovins (2004) defines it as “the portion of an energy service that is actually, not just potentially, desired and used by customers (e.g., lighting an empty room, or overheating an occupied room to the point of discomfort, is seldom useful) [sic].” Sovacool (2011) defines it as “what the end-use energy is transformed into, such as heat for a toaster or mechanical energy for agricultural processing.” Grubler et al. (2012) define it as “… the last measurable energy flow before the delivery of energy services.” Here, we adopt a definition closer to the more restrictive one cited in