ARTICLE IN PRESS

Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Greenhouse gas emission factors of purchased electricity from interconnected grids

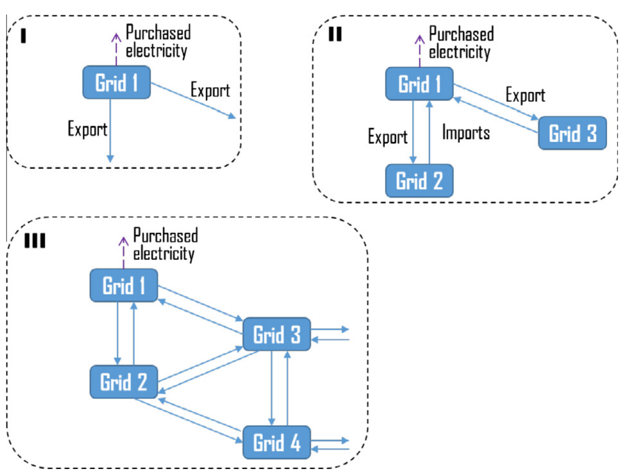
Ling Ji [a,b,1], Sai Liang [b,1], Shen Qu [b], Yanxia Zhang [b,c], Ming Xu [b,d,*], Xiaoping Jia [e], Yingtao Jia [f], Dongxiao Niu [g], Jiahai Yuan [g], Yong Hou [h], Haikun Wang [c], Anthony S.F. Chiu [i], Xiaojun Hu [j]

[a] School of Economics and Management, Beijing University of Technology, Beijing 100124, PR China
[b] School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109-1041, United States
[c] State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing 210046, PR China
[d] Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125, United States
[e] School of Environment and Safety Engineering, Qingdao University of Science & Technology, Qingdao 266042, PR China
[f] China Datang Corporation, Beijing 100032, PR China
[g] School of Economics and Management, North China Electric Power University, Beijing 102206, PR China
[h] China Electricity Council, Beijing 100761, PR China
[i] Department of Industrial Engineering, De La Salle University, Manila 1004, Philippines
[j] Energy Research Institute, Shanghai Jiao Tong University, Shanghai 200240, PR China

HIGHLIGHTS

- A new accounting framework is proposed for GHG emission factors of power grids.
- Three cases are used to demonstrate the proposed framework.
- Comparisons with previous system boundaries approve the necessity.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form 7 October 2015
Accepted 8 October 2015
Available online xxxx

Keywords:
Electricity trade
Emission factor

ABSTRACT

Electricity trade among power grids leads to difficulties in measuring greenhouse gas (GHG) emission factors of purchased electricity. Traditional methods assume either electricity purchased from a grid is entirely produced locally (Boundary I) or imported electricity is entirely produced by the exporting grid (Boundary II) (in fact a blend of electricity produced by many grids). Both methods ignore the fact that electricity can be indirectly traded between grids. Failing to capture such indirect electricity trade can underestimate or overestimate GHG emissions of purchased electricity in interconnected grid networks, potentially leading to incorrectly accounting for the effects of emission reduction policies involving purchased electricity. We propose a "Boundary III" framework to account for emissions both directly and

* Corresponding author at: 440 Church St., Ann Arbor, MI 48109-1041, United States. Tel.: +1 (734)763 8644; fax: +1 (734)936 2195.
E-mail address: mingxu@umich.edu (M. Xu).
[1] These authors contributed equally.

http://dx.doi.org/10.1016/j.apenergy.2015.10.065
0306-2619/

Please cite this article in press as: Ji L et al. Greenhouse gas emission factors of purchased electricity from interconnected grids. Appl Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.10.065

Input–output analysis
Greenhouse gas
Grid

indirectly caused by purchased electricity in interconnected gird networks. We use three case studies on a national grid network, an Eurasian Continent grid network, and North Europe grid network to demonstrate the proposed Boundary III emission factors. We found that the difference on GHG emissions of purchased electricity estimated using different emission factors can be considerably large. We suggest to standardize the choice of different emission factors based on how interconnected the local grid is with other grids.

1. Introduction

Electricity generation is an important source of global greenhouse gas (GHG) emissions [1–3], contributing to approximately 41% of total global GHG emissions in 2012 [4]. In 2010, 5.9×10^8 MW h electricity was traded internationally, representing 3% of the global total electricity generation [5].

Accurately accounting for GHG emissions of purchased electricity is critical for both determining proper electricity prices and developing effective climate policies [6–9]. Emission factors, the amount of emissions generated due to the consumption of unitary products or services, are commonly used to estimate GHG emissions of purchased electricity. Many regulatory and voluntary carbon accounting frameworks rely on emission factors of purchased electricity. For example, the GHG Protocol specifies Scope 2 emissions as emissions generated during the production of electricity purchased by the company or organization under consideration [10]. Carbon footprint accounting for cities also uses emission factors to measure GHG emissions from urban electricity consumption [11,12]. The choice of emission factors is thus important for the effectiveness of policies targeting at reducing local electricity consumption. If the emission factor is inaccurate, the effect of reduced electricity consumption on the overall emission reduction target can be overestimated or underestimated, compromising the effectiveness of the city's emission reduction policies [13].

Ideally, emission factors need to reflect the spatial variability and temporal dynamics of electricity generation, if detailed fuel mix data for specific generators at particular time are available. In practice, however, it is challenging to obtain such detailed data. Most studies thus use emission factors representing the grid average during a certain period of time (e.g., a year) [14–16]. Important policy decisions have been made based on grid-average emission factors, especially for national and regional climate policies. This study focuses on grid-average emission factors.

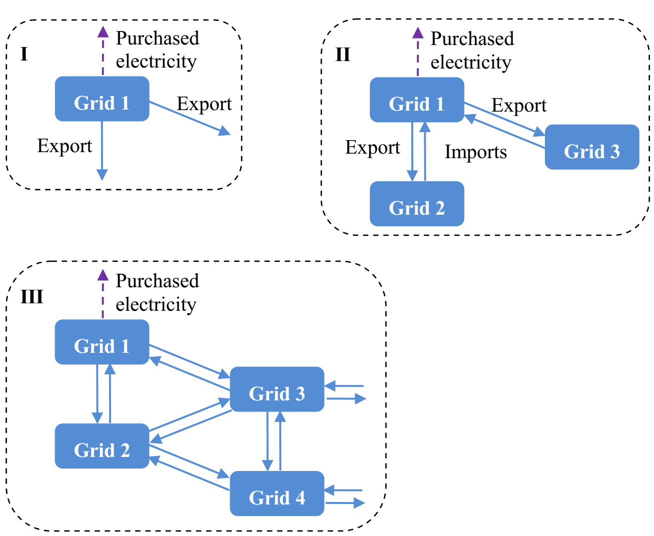


Fig. 1. Accounting boundaries for GHG emission factors of purchased electricity from interconnected grids. Dashed arrows indicate the electricity purchased by consumers in grid control area. Solid arrows indicate electricity exchange (imports and exports) between grids.

Previous studies estimate GHG emission factors of purchased electricity based on the fuel mix of the power grid from which the electricity is purchased [2,17–22]. However, indirect GHG emissions are also important to policymaking by uncovering embodied GHG burdens and potential emission burden shifts [23–26]. Choosing the appropriate system boundary for purchased electricity is thus important for the estimation of GHG emission factors.

Emission factors are commonly estimated by dividing the total emissions released from the local grid by the total electricity generated from the grid. For example, the eGrid database of the U.S. [27] and average emission factor of the Nordic region [28–30] only account for direct emissions from electricity generation and ignores emissions embodied in electricity exchanges. We denote this accounting framework as Boundary I in this study. In the real world, however, power grids do not always operate in isolation. Instead, regional grids frequently trade electricity with each other. For example, Croatia imports 38.9% of its consumed electricity from other countries in 2010, while Slovenia exports 44.0% of its generated electricity in 2010 [31,32]. Given that each grid has different fuel mix and therefore different emission profiles, Boundary I emission factors need to be adjusted to reflect the impacts of electricity trade between grids [13,30].

A commonly used approach to measure emission factors of purchased electricity from interconnected grids is accounting for emissions related to direct electricity trade with other grids on top of the emissions generated in the local grid [14,15]. In particular, total GHG emissions from the local grid are adjusted by adding emissions associated with imported electricity and deducting emissions due to exported electricity. Emissions from imported electricity are estimated based on the fuel mix of the exporting grid, assuming imported electricity is locally produced in the exporting grid. Emission factors are then calculated by dividing the adjusted emissions of the local grid by the total amount of electricity purchased from the local grid, such as CO_2 emission factors of UK's grids [33]. We denote this accounting framework as Boundary II in this study.

Fig. 1 illustrates the implications of inter-grid electricity trade on emission factors of purchased electricity depending on different accounting boundaries. In particular, Boundary I assumes the isolation of individual grid, using fuel mix of the grid which electricity is purchased from to estimate emission factors. Boundary II extends Boundary I by taking into account immediate electricity imports and exports, but assuming imported electricity is entirely produced by the exporting grid. However, imported electricity from a particular grid is in fact a blend of electricity produced by many grids, including the exporting grid itself and other grids selling electricity to it. Therefore, using Boundary II emission factors may lead to a situation similar to "carbon leakage" between countries due to international trade [34], especially when the inter-grid electricity trade is intensive. For instance, if a particular grid imports significant amount of electricity from a neighboring grid