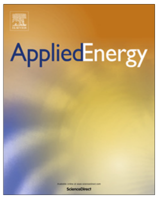
ARTICLE IN PRESS

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

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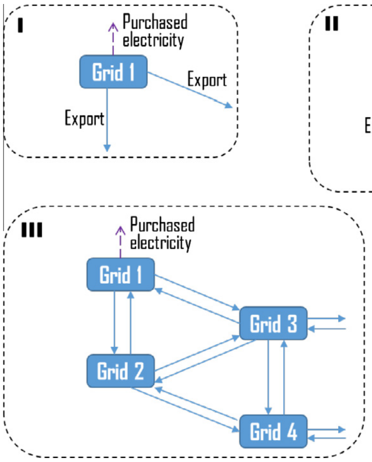
## HIGHLIGHTS

- 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

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http://dx.doi.org/10.1016/j.apenergy.2015.10.065
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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.

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## 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, $5.9 \times 10^8$ 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.

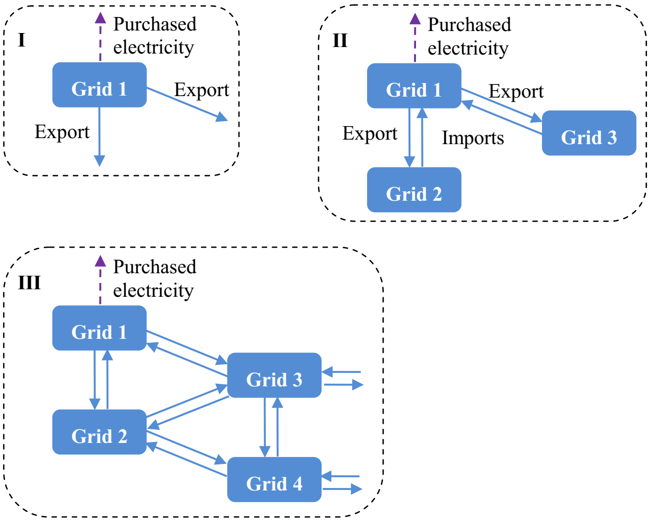

**Fig. 1.** Accounting boundaries for GHG emission factors of purchased electricity from interconnected grids. Dashed arrows indicate the electricity purchased by consumers in grid control area. Solid arrows indicate electricity exchange (imports and exports) between grids.

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

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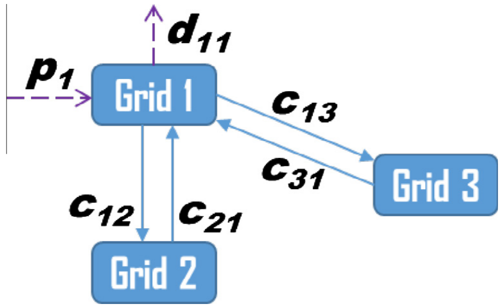

**Fig. 2.** Electricity balance of grid 1 in a three-grid network. The notation $p_1$ stands for electricity generated by grid 1; $c_{21}$ and $c_{31}$ represent imported electricity from grids 2 and 3 by grid 1; $c_{12}$ and $c_{13}$ are exported electricity from grid 1 to grids 2 and 3; $d_{11}$ represents electricity consumed by final users in grid 1.

which, in turn, imports intensively from a third grid in which the fuel mix is dominated by coal, using either Boundary I or Boundary II emission factors underestimates GHG emissions due to electricity purchased from this particular grid, as a result of not considering the indirect import of coal-dominated electricity from the third grid.

We propose in this research an alternative accounting framework to measure emission factors of purchased electricity by fully capturing the direct and indirect effects of electricity trade between multiple interconnected grids (Boundary III in Fig. 1). Note that this framework only concerns accounting for emission factors of purchased electricity as a fact that has already happened, but does not intend to predict or forecast changes of emissions due to changes of electricity consumption or production. Also, the proposed framework focuses on grid-average emission factors instead of detailed generator-specific, time-resolved emission factors.

We demonstrate this framework using three case studies on a national grid network in China, an international grid network on the Eurasian Continent, and the electricity market in North Europe. While this study is specifically for GHG emissions, the Boundary III accounting framework can also be generally applied to estimate aggregated emissions of other pollutants for purchased electricity from interconnected grids. The main contribution of this study is thus a new framework for tracking the broader impacts of inter-grid electricity trade on emission accounting. The widespread adoption of this framework could help standardize emission accounting for purchased electricity.

## 2. The "Boundary III" framework for GHG emission factors for interconnected grids

We use a conceptual three-grid network to briefly explain the Boundary III framework (Fig. 2), while more details can be found in the Supporting Information (SI). Taking grid 1 as an example, for a given period of time (e.g. a year), it receives electricity generated by generators within grid 1 (or electricity produced by grid 1), denoted by $p_1$, as well as electricity imported from other grids, denoted by $c_{21}$ and $c_{31}$. On the other hand, grid 1 sells electricity to its final users for consumption (purchased electricity), denoted by $d_{11}$, and to other grids, denoted by $c_{12}$ and $c_{13}$. It is important to note that $d_{11}$ is not the electricity locally generated in grid 1 for local users, which is often unknown or difficult to know. It is a blend of electricity as the result of electricity exchanges between grid 1 and other grids. Without considering transmission and distribution losses, the electricity inputs to a grid equal to its electricity outputs, or $p_1 + c_{21} + c_{31} = c_{12} + c_{13} + d_{11}$. Similarly, one can derive the balance equations for other grids using similar notations.

Define $\mathrm{C} = \begin{bmatrix} 0 & c_{12}-c_{21} & c_{13}-c_{31} \\ c_{21}-c_{12} & 0 & c_{23}-c_{32} \\ c_{31}-c_{13} & c_{32}-c_{23} & 0 \end{bmatrix}$, $\mathrm{P} = [p_1, p_2, p_3]^T$, $\mathrm{D} = [d_{11}, d_{22}, d_{33}]^T$, and $\mathrm{R} = \mathrm{C} \times (\mathrm{diag}(\mathrm{P}))^{-1}$. One can then express the vector of electricity generation P as:

$$\mathrm{P} = (\mathrm{I} - \mathrm{R})^{-1}\mathrm{D} \tag{1}$$

The above equation is similar to the input–output model widely used to examine the interconnectedness of sectors of an economy [35] (derivation in SI). In particular, matrix C describes net electricity trade flows among grids; vector P represents the electricity generated by each grid; vector D stands for the electricity purchased by final users in each grid-controlled area; I is the identity matrix, matrix $(\mathrm{I}–\mathrm{R})^{-1}$ indicates total electricity produced in each grid that is directly and indirectly imported to a particular grid due to unitary electricity purchased from it, and the notation "diag" diagonalizes a vector. We define elements of matrix R, $r_{ij}$, as direct electricity requirement coefficients, measuring the net electricity exchange from grid $i$ to grid $j$ due to unitary electricity generation in grid $j$. Note that our method is a variation of standard input–output models which essentially characterize the physical interdependences between components of an interconnected system despite usually using monetary data [35–37].

GHG emission factors for each grid can be calculated as (derivation in SI):

$$\mathrm{E} = \mathrm{F}(\mathrm{I} - \mathrm{R})^{-1} \tag{2}$$

where F is a row vector representing GHG emissions directly generated in each grid due to unitary electricity production (Boundary I emission factors). In particular, elements of vector E, $e_i$, are the total (direct and indirect) GHG emissions from all grids due to unitary electricity purchased from grid $i$. We define $e_i$ as the Boundary III emission factor for purchased electricity from grid $i$, which estimates the direct and indirect emissions from an interconnected grid system due to unitary electricity purchased from grid $i$.

For simplicity, we do not consider transmission and distribution losses in illustrating the Boundary III framework. However, electricity losses from transmission and distribution can be significant in real world, representing non-trivial amounts of electricity production and GHG emissions not reflected in final purchases. Methodologically, one can take into account transmission and distribution losses in the Boundary III framework, by adding the amount of transmission and distribution losses to traded electricity $c_{ij}$ and production $p_i$. In reality, line losses are a function of temperature, distance, and line capacity. Grids far away from an importing grid would have more line losses than one adjacent to an importing grid. Integrating the exact modeling of transmission and distribution losses into our Boundary III framework is an important future research avenue.

Comparing to commonly used Boundary I emission factors, Boundary III emission factors only need limited additional data to calculate. In particular, one needs inter-grid electricity trade data to construct matrix C, which are generally available for major countries and regions. In case that electricity trade data for particular trade flows are not available, one can use mass balance principles to estimate the missing data, i.e., electricity imported plus electricity generated equals to electricity consumed plus electricity exported.

In particular, there are re-exports of electricity for a grid which are hard to quantify because electricity generated by a grid itself and imported from other grids are blended as a pool and then sold to consumers served by this grid and other grids. It is difficult to identify which part of the exported electricity is pass-through. However, if such data are available, our Boundary III framework can account for re-exports, simply by considering the re-exported

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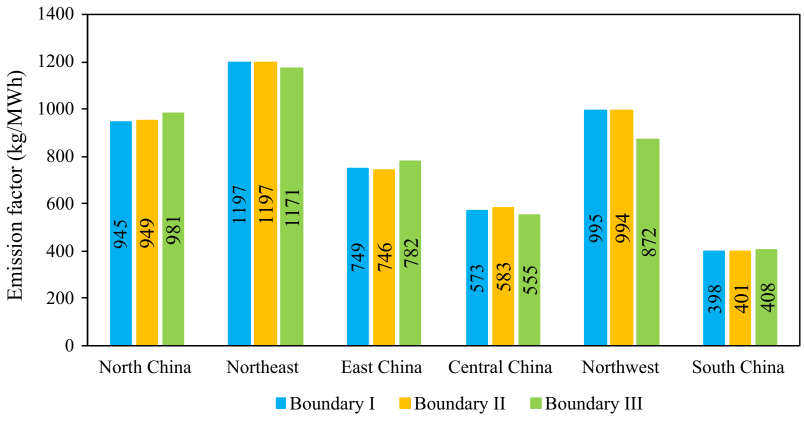

**Fig. 3.** GHG emission factors of purchased electricity from China's regional grids under different accounting boundaries. Results supporting this graph are listed in Table S3 in the SI.

electricity as the electricity exported directly from the producing grid to the consuming grid, and adjusting the inter-grid trade matrix C accordingly.

We use three cases to demonstrate Boundary III emission factors and compare them with results using Boundary I and II: a national grid network in China in 2011, an international grid network on the Eurasian Continent in 2010, and the North European electricity network in 2010. Data sources for the case studies are described in the SI. Given that the main purpose of this paper is to demonstrate the Boundary III emission factor, transmission and distribution losses are not considered in the case studies. Moreover, Boundary III emission factors are calculated based on Boundary I emission factors, as shown in Eq. (2). There are usually uncertainties in Boundary I emissions factors [38]. Calculating grid-specific and more accurate Boundary I emissions factors is important for the accuracy of Boundary III emissions factors in future studies.

## 3. Case study

### 3.1. Case 1: GHG emission factors of purchased electricity in China in 2011

China's power grid is divided into six regional grids: North China, Northeast, East China, Central China, Northwest, and South China (Table S1). Fig. 3 shows GHG emission factors of electricity purchased from China's regional grids based on the three accounting boundaries. Three GHG emissions including $CO_2$, $CH_4$, and $N_2O$ are considered by converting all emissions into kg $CO_2$-equivalent using global warming potentials [39]. Overall, the difference between the three boundaries is marginal, mostly below 5%. This is due to the fact that only a small portion of electricity is traded between regional grids in China (3.17% in 2011). However, the Boundary III emission factor of the Northwest grid is 12.37% and 12.23% lower than the Boundary I and Boundary II emission

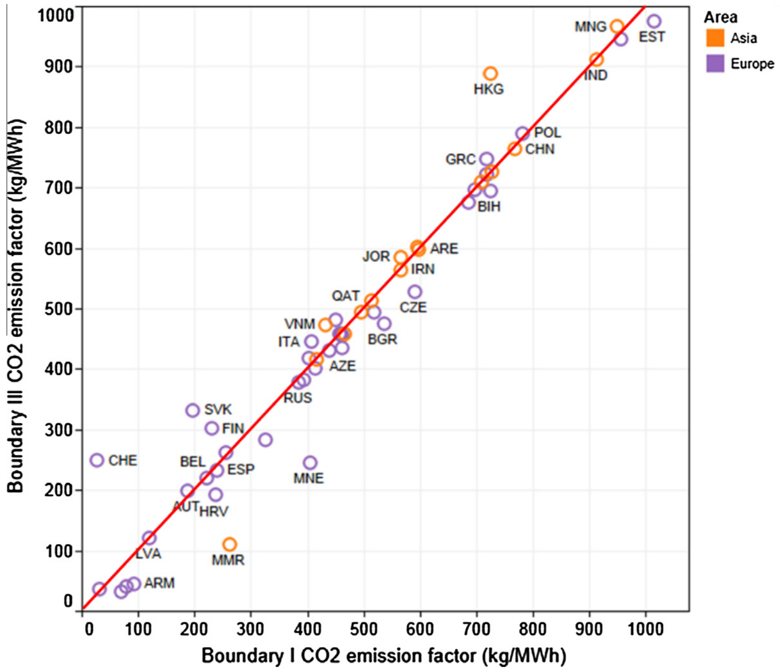

**Fig. 4.** Boundary I and Boundary III $CO_2$ emission factors of purchased electricity for each country on the Eurasian Continent in 2010. Results supporting this graph are listed in Table S7 in the SI.

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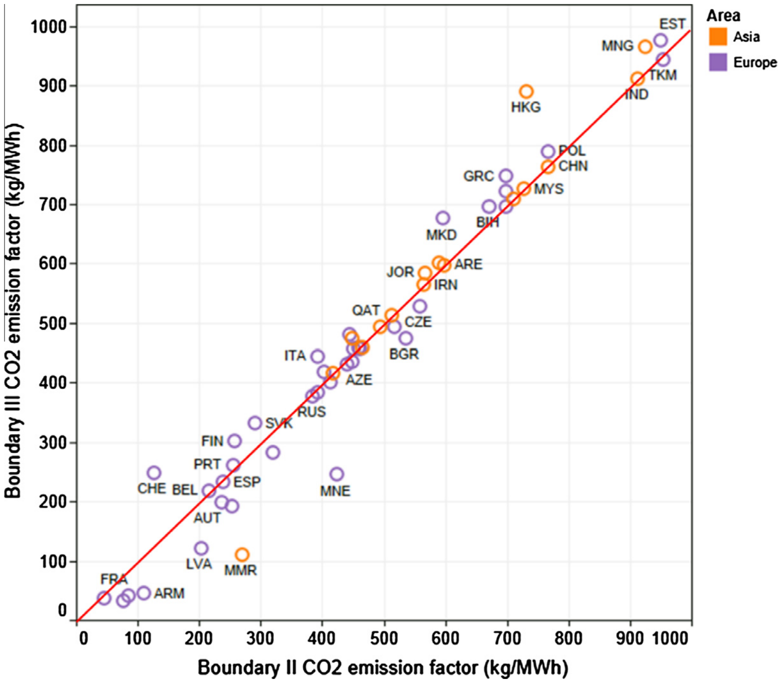

**Fig. 5.** Boundary II and Boundary III $CO_2$ emission factors for purchased electricity for each country on the Eurasian Continent in 2010. Results supporting this graph are listed in Table S7 in the SI.

factors, respectively. In 2011, the Northwest grid exports 15.7 and 48.6 TW h electricity to the Central China and North China grids, and imports only 1.4 TW h from the Central China grid (Fig. S2). Since the Central China grid is relatively less carbon-intensive than the Northwest grid, the Boundary II framework slightly lowers GHG emission factor of purchased electricity from the Northwest grid. In addition, the two major trading partners of the Northwest grid, Central China and North China grids, both trade significant amounts of electricity with other grids, which indirectly affects the electricity blend of the Northwest grid. Such indirect effects are captured by the Boundary III framework, further lowering the GHG emission factor of purchased electricity from the Northwest grid.

The difference that various emission factors make can be significant, even though the relative differences among them are less significant. For example, GHG emissions due to electricity purchased from the Northwest grid under Boundary III are 48.0 Mt and 47.4 Mt less than those under Boundary I and Boundary II, respectively (Table S4). Such differences are equivalent to national GHG emissions of Finland (42.5 Mt) and Switzerland (46.8 Mt) in 2011 [40].

We conduct a sensitivity analysis to evaluate the impact of data uncertainty on the results. As shown in Tables S5 and S6, changes in Boundary I emission factors of particular grids have limited impacts on Boundary III emission factors of other grids, except for those grids themselves. This reflects the fact that inter-grid electricity trade is not significant comparing to the total electricity production and consumption of each grid in China, which also leads to similar emission factors using different accounting frameworks (Fig. 3). However, Boundary III emission factors (Table S6) are more sensitive to data uncertainty than Boundary II emission factors (Table S5), due to the cumulative impact of electricity trade.

### *3.2. Case 2: $CO_2$ emission factors of purchased electricity on the Eurasian Continent in 2010*

Fig. 3 shows the electricity trade between 53 major countries/regions on the Eurasian Continent, including 37 European countries and16 Asian countries (Table S7). Note that electricity trade mainly happens between neighboring countries due to geographical constraints. We only account for $CO_2$ emissions in this study due to limited data for other GHGs. In particular, $CO_2$ emission factors for the Boundary I framework are from the IEA [4]. Generally, the average Boundary I emission factor of European countries (415 kg $CO_2$/MW h) is much lower than that of Asian countries (606 kg $CO_2$/MW h).

Fig. 4 shows the comparison of Boundary I and Boundary III $CO_2$ emission factors. The red solid line indicates that the Boundary I emission factor is equal to the Boundary III emission factor. Most countries are found above the red solid line, implying that the Boundary III emission factor is higher than the Boundary I emission factor. These countries import more carbon-intensive electricity from other countries, leading to higher Boundary III emission factors. In particular, Switzerland, Slovakia, and Finland have the largest differences between Boundary I and Boundary III emission factors. The Boundary III emission factors are 823%, 69%, and 32% higher than the Boundary I emission factors in Switzerland, Slovakia, and Finland, respectively (Table S7). These countries, together with other countries that appear above the red solid line, import more carbon-intensive electricity directly and indirectly.

On the other hand, countries located below the red solid line directly and indirectly import less carbon-intensive electricity, leading to lower Boundary III emission factors. In particular, the Boundary III emission factors of Myanmar, Georgia, and Armenia are 58%, 52%, and 50% lower than their Boundary I emission factors, respectively (Table S7).

Countries along the line have similar Boundary I and Boundary III emission factors. They are either large countries for which traded electricity is relatively less significant, such as China, Russia, and India, or countries which directly and indirectly import electricity from grids with similar carbon intensities, such as Latvia, Macedonia, and United Arab Emirates.

Fig. 5 shows the comparison of Boundary II and Boundary III $CO_2$ emission factors. The majority of countries are away from the red solid line which indicates Boundary III emission factors

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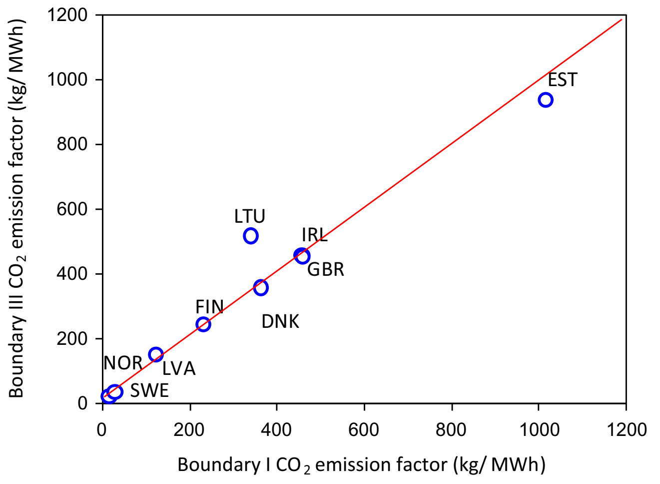

**Fig. 6.** Boundary I and Boundary III $CO_2$ emission factors of purchased electricity for major North European countries in 2010. Results supporting this graph are listed in Table S11 in the SI.

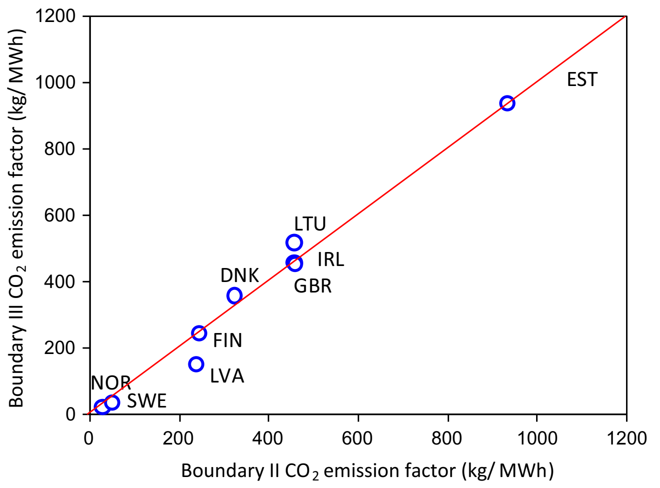

**Fig. 7.** Boundary II and Boundary III $CO_2$ emission factors for purchased electricity for major North European countries in 2010. Results supporting this graph are listed in Table S11 in the SI.

are different from Boundary II emission factors for those countries. In particular, the differences between the Boundary III and Boundary II emission factors in Switzerland, Hong Kong, and Finland are the highest among all countries with higher Boundary III emission factors, 50%, 18%, and 15%, respectively. This indicates that electricity indirectly imported by these countries which is captured by Boundary III framework is more carbon-intensive than directly imported electricity directly which Boundary II framework only captures.

On the other hand, the Boundary III emission factors of Myanmar, Armenia, and Georgia are 144%, 135%, and 129% lower than their Boundary II emission factors, the largest difference among all countries with lower Boundary III emission factors. This indicates that these countries directly import carbon-intensive electricity; but low carbon-intensive electricity indirectly imported by these countries makes their Boundary III emission factors lower.

Higher Boundary III emission factors comparing to Boundary II emission factors indicate importing more carbon-intensive electricity indirectly, while lower Boundary III emission factors imply indirect imports of less carbon-intensive electricity.

With different emission factors, the difference on $CO_2$ emissions due to purchased electricity can be significant. For example, $CO_2$ emissions of electricity purchased in Switzerlandin 2010 under Boundary III are 26.8 Mt higher than those under Boundary I (Table S8). This difference is larger than national $CO_2$ emissions of Norway (21.9 Mt) or Sweden (21.5 Mt) in 2010 [40]. Moreover, $CO_2$ emissions of electricity purchased in France under Boundary III is 22.2 Mt lower than those under Boundary II (Table S8), also equivalent to Norway's national $CO_2$ emissions in 2010.

We also conduct a sensitivity analysis to evaluate the impact of data uncertainty on the results of this case (Tables S9 and S10). The impact of data uncertainty on emission factors for this case is larger than that for the first case, mostly due to more intensive inter-grid electricity trade in the second case. Similarly, Boundary III factors are more sensitive to data uncertainty than Boundary II factors.

### *3.3. Case 3: $CO_2$ emission factors of purchased electricity in North Europe in 2010*

With the deregulation of electricity market, Nord Pool Spot has become a successful leading power market in Europe, which provides a free electricity trade platform for 380 members from about 20 countries. Here we focus on the large-scale electricity trade among major North European countries (Fig. S4). The $CO_2$ emission factor of generated electricity (Boundary I) in Estonia is the largest (1,014 kg/MW h), while those in Norway and Sweden are as low as 17 kg/MW h and 30 kg/MW h, respectively.

Fig. 6 shows the comparison of Boundary I and Boundary III $CO_2$ emission factors, where most dots lie near the red solid line. For most countries, the differences between Boundary I and Boundary III are quite small. On the other hand, for Lithuania, the $CO_2$ emission factor of purchased electricity in Boundary III is significantly higher than that in Boundary I. This is because Lithuania is a net importing country which imports large amounts of electricity from Estonia with a higher $CO_2$ emission factor. Meanwhile, since Boundary III framework considers imported electricity, any imported electricity from other countries decreases the $CO_2$ emission factor of purchased electricity in Estonia. Thus, under Boundary III framework, the actual $CO_2$ emissions caused by electricity consumption in Estonia are lower than its $CO_2$ emissions estimated under Boundary I framework (Table S12).

Fig. 7 shows the comparison between Boundary II and Boundary III $CO_2$ emission factors. Half of the countries still lie on the red solid line, indicating marginal difference between Boundary II and Boundary III. Especially, for Norway, Sweden, Finland, Ireland and United Kingdom, the estimated $CO_2$ emission factors are quite close. This is due to the fact that the $CO_2$ emission factors of generated electricity of their main trade partners are close. For Latvia, the $CO_2$ emission factor of Boundary II is larger than that of Boundary III, while for Denmark the $CO_2$ emission factor of Boundary III is slightly higher than that of Boundary II.

Total $CO_2$ emissions of purchased electricity and differences among different boundary frameworks for each main North Europe country are listed in Tables S11 and S12, respectively. For countries like United Kingdom, Ireland, and Denmark, $CO_2$ emissions estimated by Boundary III framework are almost the same as those by Boundary I. However, for Norway, Lithuania, Sweden, and Latvia, actual $CO_2$ emissions of purchased electricity estimated by Boundary III are much higher than estimations using their own $CO_2$ emission factors of generated electricity (Boundary I). This is because the imported electricity is less clean than locally generated electricity. In addition, sensitivity analysis is also conducted to evaluate the impact of primary emission data (Boundary I emission factors) on the results of Boundary II and III emission factors (Tables S13 and S14). In general, Boundary III emission factors

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are less sensitive to the uncertainty of primary emission data, mainly because Boundary III emission factors depend on more variables (literally emissions of all other grids) than Boundary II emission factors (only emissions of direct trading grids).

## 4. Discussion and conclusions

The proposed Boundary III method for measuring GHG emission factors of purchased electricity can more practically calculate carbon footprints of power grids, and therefore has a number of important climate policy implications. By implementing the Boundary III method, GHG emission factors of purchased electricity from particular grids can be significantly different from those calculated using traditional Boundary I or Boundary II methods. For grids that indirectly import more (less) carbon-intensive electricity from other grids, GHG emission factors will increase (decrease). The different GHG emission factors can significantly change the emission profiles of companies, organizations, cities, regions, or countries. This can lead to incorrect emission baseline accounting and thus hinder the efforts of climate policy to mitigate GHG emissions.

Take an example of a country (or city, company, etc.) that has lower Boundary III emission factor than Boundary I and II emission factors. Using Boundary I or II emission factor for estimating emissions of purchased electricity can lead to overestimation of the effect of reduced electricity consumption, because the local grid indirectly imports less carbon-intensive electricity from other grids. On the other hand, if the Boundary III emission factor is higher than Boundary I or II emission factor, using Boundary I or II emission factor may underestimate the effect of emission reduction from reduced electricity consumption.

By comparing emission factors of grids similar to Figs. 4 and 5, one can easily identify grids that inter-grid electricity trade has the largest impacts on. In particular, a country lying farther away from the solid line in Figs. 4 and 5 indicates that there is a greater gap between its Boundary III emission factor and Boundary I or II emission factor. Thus, the effectiveness of policies in those countries is more sensitive to the choice of boundaries for the estimation of emission factors.

The case studies presented in this paper do not consider transmission and distribution losses, given the fact that traded electricity is generally a small fraction of the total electricity generation or consumption in regional grids in the case studies. However, when traded electricity has significant impacts on emission factors, such as those countries far away from the red solid lines in Figs. 4 and 5, transmission and distribution losses become more important for the accuracy of emission factor estimation. Moreover, temporal dynamics of power generation is not considered, which represents an interesting future research avenue if such necessary data are available.

The Boundary III emission factor links electricity consumption with generation at the grid level. However, it still does not fully capture the spatial separation of electricity consumption and generation. Ideally, one needs to know which power plants meet the electricity demand and the fuel mix during the consumption period. This requires access to detailed data on electricity generation, dispatch, transmission, and demand. These data can then be used to estimate electricity flows from specific generators to particular regions at any given time. Unfortunately, such data are often proprietary and computationally intensive to process and analyze. Even with the detailed data, uncertainty of emission factors would still exist, although reduced [13]. However, such data, if available, can help evaluate the uncertainty of Boundary III emission factors using Monte Carlo simulations based on the statistical distributions of Boundary I emission factors for each grid and the amount of traded electricity during the study period.

A standardized method should be developed to guide using various emission factors for purchased electricity. For example, Boundary I and II emission factors may be sufficient for electricity purchased from relatively independent grid. For highly interdependent grids with distinct fuel mixes, Boundary III emission factors may be more appropriate. Nonetheless, if such standard is nonexistent, we suggest that a range of emission factors should be used for calculating emissions from purchased electricity to report the associated uncertainty.

While this study is specific for GHG emissions, the Boundary III accounting framework can also be applied to estimate aggregated emissions for other pollutants due to purchased electricity from interconnected grids. Because the impacts of non-GHG emissions are more local, results on aggregated emissions alone have limited implications. However, one can potentially conduct a structural path analysis [41,42] based on the Boundary III framework to quantify local environmental impacts due to non-GHG emissions and identify important electricity supply chains contributing to particular local impacts.

Last but not least, the Boundary III framework can potentially bring other opportunities for applying input–output analysis techniques to better understand the impact of inter-grid electricity trade on electricity-related environmental impacts. For example, using structural decomposition analysis [43–46] one can examine the relative contributions of electricity trade and electricity consumption patterns to the change of aggregated emissions during a period of time. Using linkage analysis [47,48] can identify individual grids that are important to the network-wide emission profiles.

## Acknowledgments

Ling Ji thanks the financial support of China Scholarship Council (CSC). Sai Liang and Shen Qu thank the support of the Dow Sustainability Fellows Program.

## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2015.10.065.

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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