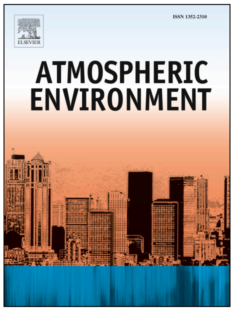

Greenhouse gas emission accounting approaches in electricity generation systems: a review

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Abstract

Globally, electricity systems are responsible for two-thirds of total greenhouse gas (GHG) emissions. This area has become one of the main focuses for a wide range of scientific communities, and a large number of articles have been published that reported GHG emissions from the electricity sector using different approaches. Even though some review articles have been published on particular GHG emissions approaches, such as life cycle assessment (LCA), studies that investigated overall approaches are much rarer. A scoping review of these GHG emissions accounting approaches has thus been conducted in this study to explore their limitations and indicate possible future scope. From the review, it was found that the majority of the studies considered the LCA approach to investigate GHG emissions from electricity systems. Although the time-varying carbon intensity approach has potential features, it has received less attention. Furthermore, this review has highlighted some issues that need to be addressed by any new or existing approach that would deal with GHG emissions accounting in the near future. In addition, this review would be helpful for policymakers and electricity authorities when selecting appropriate approaches in accounting GHG emissions from the electricity system.

Keywords: GHG emission accounting; Methods and approaches; Electricity systems; Carbon intensity; Emissions and atmosphere.

1. Introduction

In recent years, focus on greenhouse gas (GHG) emissions reduction has increased dramatically, involving scientists, academics, policymakers, and industry, and in particular, the electricity industry, as electricity generation systems are the largest single source of GHG emissions globally (Bazán et al., 2018; Cellura et al., 2018; Howard et al., 2017; Garcia and Freire, 2016; Atilgan and Azapagic, 2015). It was also found that compared to many other sectors, electricity generation systems is the one where decarbonisation can be achieved at an acceptable pace (Staffell, 2017; Vedachalam et al., 2017; Morvaj et al., 2017). Although the potential of GHG emissions reduction has been proven to overcome the negative impacts of climate change, as well as to ensure a sustainable global low-carbon future, the measures that have been taken for such reduction seem limited in scale (Hu et al., 2018; Foster et al., 2017; Williams et al., 2012). One reason is the appropriate monitoring, reporting, and verification (MRV) process, particularly, monitoring and reporting as identified by the International Energy Agency Greenhouse Gas Research and Development (IEA-GHG R&D) programme (IEA-GHG R&D, 2018). Due to diverse GHG emissions accounting methodologies, none of the present approaches is well suited for GHG emissions accounting (Bruckner et al., 2014). For example, the IEA-GHG R&D programme has reported that there is uncertainty towards the deployment of CO_2 capture and utilisation (CCU) technology with respect to GHG emissions reductions due to the lack of appropriate accounting methods and MRV processes in place, which are necessary to track, calculate, and report the benefits that would be achieved by deploying CCU technology (IEA-GHG R&D, 2018). Therefore, a review is indispensable in order to identify the available approaches of GHG emissions accounting in the electricity generation systems.

Essentially, a country's ability to monitor, measure, and review GHG emissions from the electricity generation sector enables it to engage and act accordingly towards a national as well as a global low-carbon future, as two-thirds of global GHG emissions is the consequence of the energy sector's activities, which includes the electricity generation systems (IEA, 2017). Hence, an informative and robust GHG emissions reporting approach needs to be developed along with proper methodology (Bruckner et al., 2014). However, despite the evidence that GHG emissions can vary considerably according to the time of day or season (Khan et al., 2018), methods of assessing GHG emissions from electricity generation do not currently account for variance over time. According to the IEA-GHG R&D programme's latest report, GHG emissions accounting considers two approaches: ex ante-assessment and ex post-assessment (IEA-GHG R&D, 2018). Ex ante-assessment involves the estimation of the full range of GHG emissions, which includes extraction, manufacture, transport, construction, and end of life associated with the product or activity. On the other hand, ex post-assessment, referred to as the MRV method, involves real-time estimation of GHG emissions over a certain period of time (e.g., annually). The latter approach is used towards carbon abatement-related policymaking and international reporting. However, due to the use of inappropriate emission factors, taking into account different activities that cause emissions, the nature of emissions, and difficulties in defining the boundaries have made emissions calculation a challenging task.

Apart from this, approaches used in the scientific studies that considered GHG emissions from the electricity sector varied significantly, which may result in different findings even though they might have used the same datasets (Amponsah et al., 2014; Soimakallio et al., 2011). A literature search reveals that there are some studies that reviewed a particular method of assessments such as life cycle assessment (LCA) for GHG emissions analysis in electricity systems (Muench, 2015; Turconi et al., 2013; Soimakallio et al., 2011; Lenzen, 2008). Nevertheless, it seems that no previous studies have considered reviewing overall approaches that are used to assess GHG emissions in the electricity sectors, in particular, electricity generation. The objective of this paper is thus to review available methods and methodologies that have been used to assess GHG emissions from the electricity sector and explore the methodological knowledge gap that may exist in the literature.

The rest of the paper is organized as follows: section 2 describes the methodology used for this review. Section 3 discusses international rules of GHG emissions accounting. Section 4 presents available approaches that have been used in the literature to report GHG emissions from the electricity sector. Section 5 discusses the findings and identifies potential areas that need to be explored in future research. The final section concludes the paper.

2. Methodology

This is a scoping review (Grant and Booth, 2009), thus, it has considered a range of published peer-reviewed journal and conference articles to make a preliminary assessment of the overall GHG emissions accounting approaches that have been used in the literature to report electricity generation- related emissions. Consequently it indicates the scope of future research. A standard six step scoping review methodology (Peterson et al., 2017) was followed, illustrated in Fig. 1.

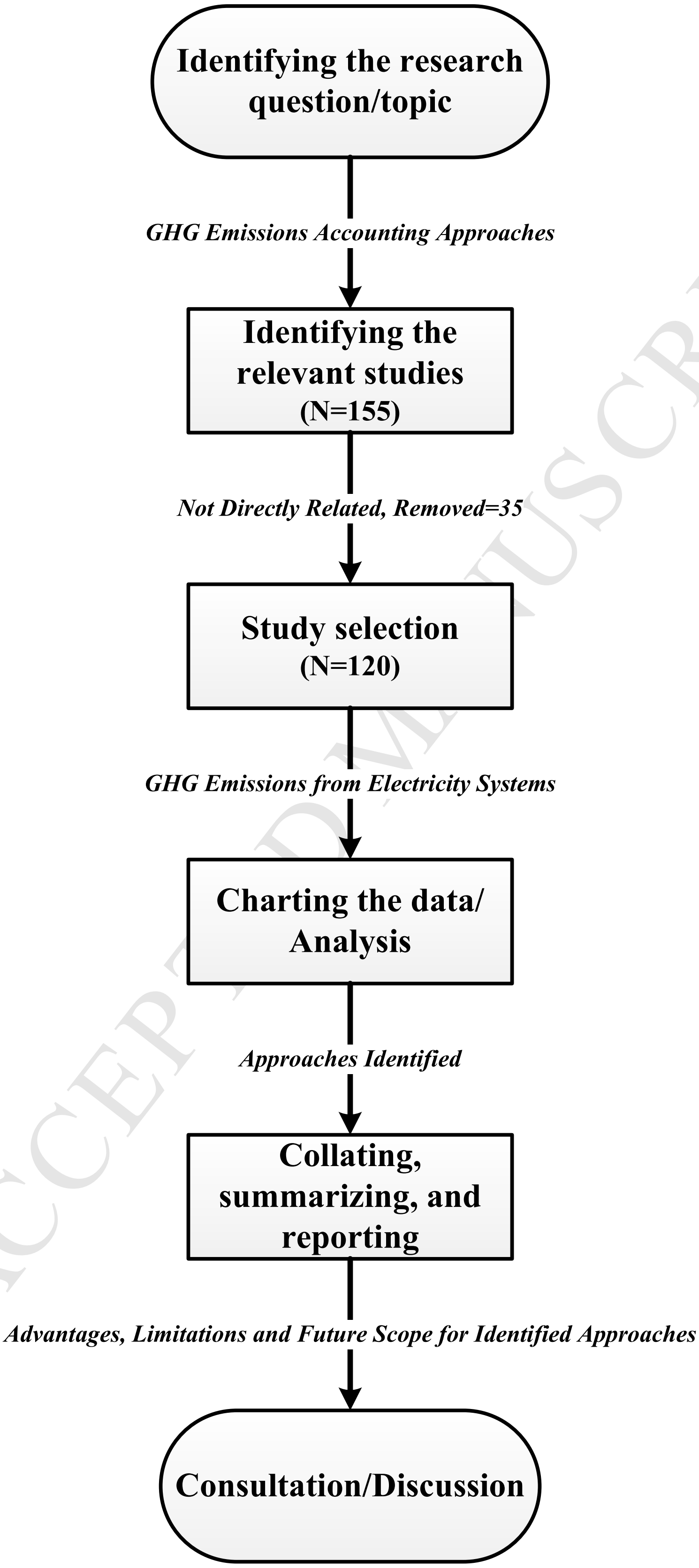

Fig. 1. Methodology used for this scoping review.

The review process began by exploring the topic in the scientific literature through sciencedirect.com, using relevant keywords. The keywords used for the search were: greenhouse gas emissions and electricity; greenhouse gas and electricity; GHG and electricity; emissions and electricity; greenhouse gas, electricity; GHG methods and electricity; carbon intensity and electricity.

While searching, the word ‘electricity’ was kept constant as the review is focused on GHG emissions from the electricity sector only. The search resulted in 155 studies; during the selection step, it was found that 35 studies were not directly associated with the electricity generation, and were removed from the analysis, leaving a total of 120 studies that were considered for this review. After completion of the review process, findings are presented and discussed.

3. GHG emissions accounting

There are two types of emissions in the electricity sector: direct and indirect emissions. According to the GHG Protocol[1], "*the emissions from the sources that are owned or controlled by the reporting entity*" are known as direct emissions, while "*emissions that are a consequence of the activities of the reporting entity, but occur at sources owned or controlled by another entity*" are indirect emissions. These direct and indirect emissions are further categorized as scope-1, scope-2, and scope-3. Direct GHG emissions, electricity indirect GHG emissions, and other indirect GHG emissions are associated with scope-1, scope-2, and scope-3, respectively[2].

[1,2] https://ghgprotocol.org/

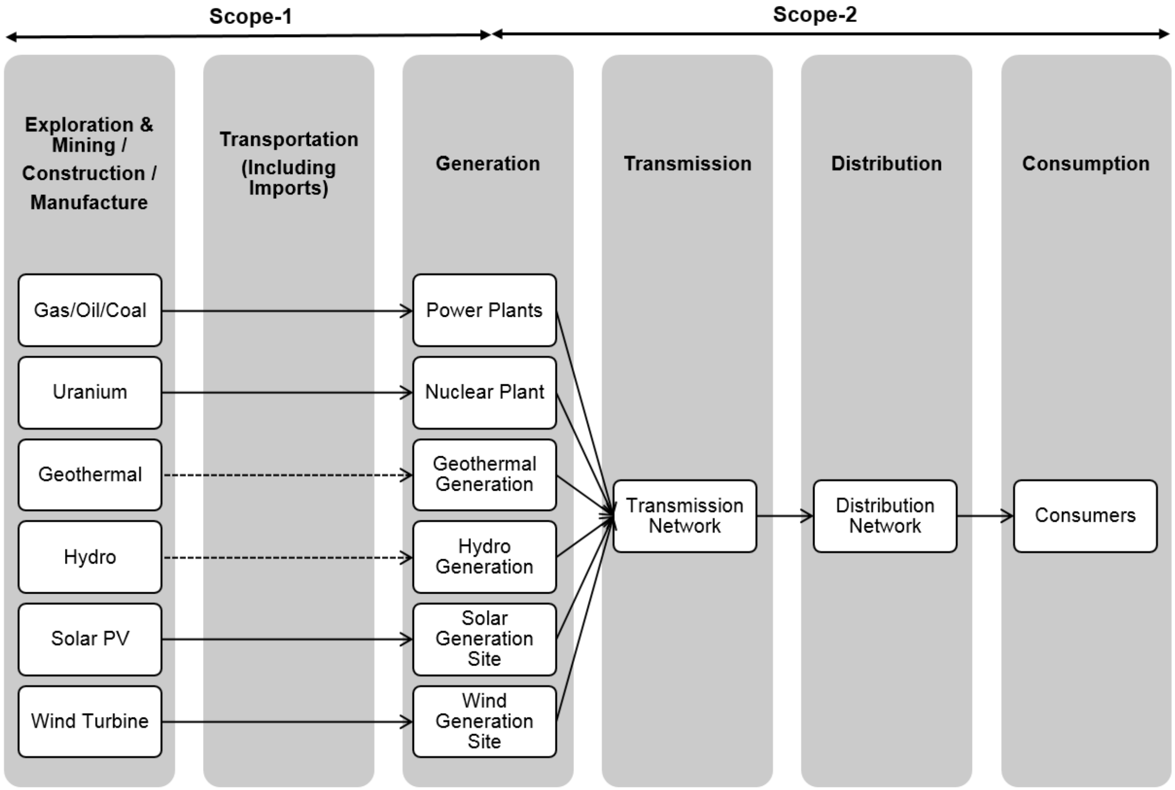

Fig. 2. Overall electricity system and GHG emissions accounting scopes. Dotted lines indicate no transportation.

Electricity systems include both scope-1 and scope-2 emissions, as shown in Fig. 2. Exploration and mining of any new fossil fuel or uranium, building geothermal or hydro plants are within scope-1, direct emissions. Manufacturing of generation technologies such as solar PV and wind turbines is also within scope-1 emissions, as is transportation that is involved either to carry fuel to the plant or import it from other countries. Part of the electricity generation process (i.e., fuel combustion) is within scope-1 and the remainder of the processes which include generation, transmission, distribution, and consumption are within scope-2 emissions.

Although there are a number of GHGs that are emitted from the electricity generation process, in general, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are regarded as the major GHGs (Bauer et al., 2018; Kumar and Sharma, 2017; IPCC, 2014). To consider all these three GHGs together, carbon dioxide equivalent (CO_2-e) is used as the unit of overall emissions, which is usually obtained by multiplying the actual amount of individual emitted gas with the global warming potentials (GWP, 100-year)[3] of 1, 28, and

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[3] GWP provides a relative measure of the heat that can be trapped in the atmosphere due to a GHG.

265 for CO_2, CH_4, and N_2O, respectively, and finally, adding them together (IEA, 2017; IPCC, 2014).

4. Electricity associated emissions accounting approaches

4.1 Absolute emissions approach

Absolute emissions refer to quantification of the total amount of GHGs that has been emitted (in tonnes of CO_2-e) to the atmosphere over a certain period (e.g. annually) through activities such as electricity generation. Most governments and environmental organizations, as well as international bodies such as the International Energy Agency (IEA) and Intergovernmental Panel on Climate Change (IPCC) use absolute emissions for national GHG inventories, policymaking and regulatory efforts in relation to GHG emissions reduction (IEA, 2018; IPCC, 2018). Absolute emissions from electricity generation can be calculated using Eq. (1) (IEA, 2017).

$$GHG\ Emissions = \frac{CIF*SEF*TE}{\eta} \quad (1)$$

Where:

GHG Emissions: Total emissions from electricity generation (in kg CO_2-e).

CIF: Carbon intensity of the fossil fuel mix (kgCO_2-e/kWh).

SEF: Share of electricity generated from fossil fuels.

TE: Total generated electricity from the system (in kWh).

η : Fossil fuelled power plant efficiencies.

In the academic literature, a number of previous studies have reported GHG emissions from electricity generation using an absolute emissions approach (Kachoee et al., 2018; Castrejón et al., 2018; Squalli, 2017; Niet et al., 2017; Kusumadewi et al., 2017; Staffell, 2017; Vedachalam et al., 2017; Ozcan, 2016). This has often been used to evaluate emission reduction potential. Kachoee et al. (2018) found that adoption of renewable generation in the Iranian electricity systems could reduce GHG emissions by 294.6 million tonnes. A study in the USA investigated CH_4 emissions from the electricity system and found that only 0.26% CH_4 could be reduced by increasing the renewable share to 10% in the electricity system (Squalli, 2017). The dramatic increase in the renewable share along with some other factors in the British electricity sector resulted in a 46% reduction in absolute emissions for the period 2013 to 2016 (Staffell, 2017).

Absolute emissions approaches have also been used in studies on the potential for carbon capture and storage (CCS) technologies to reduce GHG emissions (Castrejón et al., 2018; Hanson and Schmalzer, 2013; Hammond et al., 2011). In Mexico, Castrejon et al. (2018) considered carbon abatement options through different scenarios in the energy sector and found that deployment of CCS technologies could potentially reduce GHG emissions in the electricity sector. Ding et al., (2017), Ozcan (2016) and Taseska et al., (2011) estimated GHG emissions from the electricity sector using this approach for China, Turkey and Macedonia. India's future grid expansion plan and future CO_2 emission scenarios have also been assessed using absolute emissions (Shearer et al., 2017). Other studies also used the absolute emissions method in the electricity sectors in a variety of different contexts (Pleßmann and Blechinger, 2017; Grande-Acosta and Islas-Samperio, 2017; Usubiaga et al., 2017; Khondaker et al., 2016; Guemene Dountio et al., 2016; Cho et al., 2016; Clancy et al., 2015).

In summary, the absolute emissions assessment approach has been used in many studies to track emissions changes, compare scenarios and assess GHG emissions abatement options.

4.2 Life cycle assessment approach

A large and growing body of literature has investigated GHG emissions from electricity generation systems using life cycle assessment (LCA) (Q. Song et al., 2018; Chen et al., 2017; Rajaeifar et al., 2017; Li et al., 2017; Walker et al., 2017; Xu et al., 2016; Su and Zhang, 2016; Thornley et al., 2015; Muench, 2015; Hardisty et al., 2012; Martínez et al., 2012; El Hanandeh and El Zein, 2011). LCA is an environmental assessment method that includes all the environmental impacts associated with the product's entire life, that is, raw material extraction to waste materials deposition after its life expiration as shown in Fig. 3 (Bauer et al., 2018). The LCA method considers either absolute emissions [as per Eq. (1)] or average emission intensity, or often both. When applied to electricity generation systems, emission intensity (in gCO_2-e/kWh) is defined as the amount of emissions per unit of electricity generation over a fixed period of time (e.g., annually) (IEA, 2017). This is shown in Eq. (2).

$$Emission\ Intensity = \frac{CO_{2-e}\ emissions\ from\ fossil\ fuelled\ electricity\ generations}{Total\ electricity\ generated\ from\ all\ sources} \qquad (2)$$

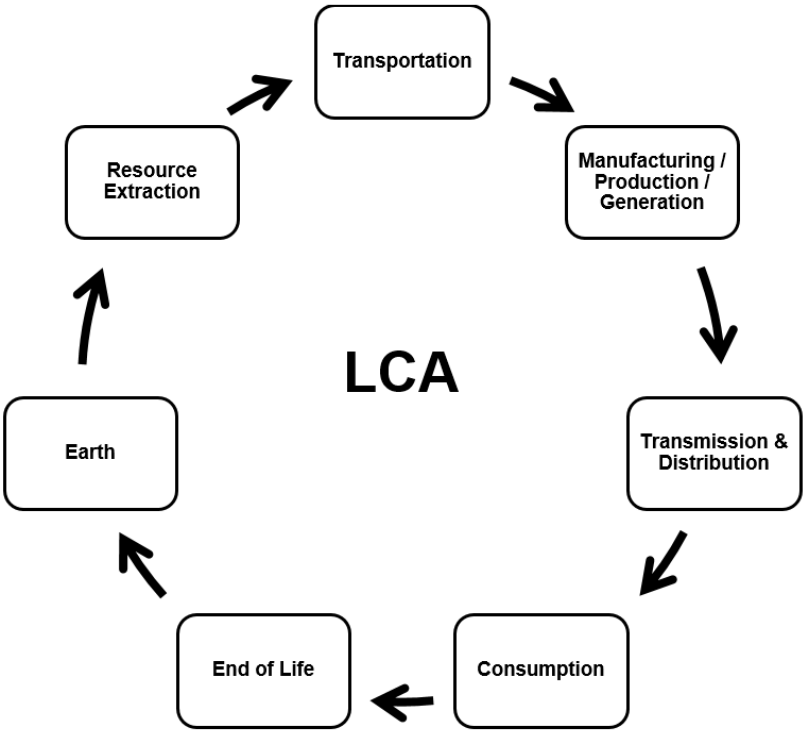

Fig. 3. Life cycle assessment method for electricity system.

In the electricity sector, LCA has often been used to compare different generation technologies and their associated GHG emissions. For example, in some early studies, Hondo (2005) and Weisser (2007) evaluated GHG emissions from different generation technologies, which included fossil fuel, nuclear, and renewable generations. In particular, Hondo (2005) assessed GHG emissions from nuclear, wind, and solar photovoltaic technologies and compared these with different fossil fuelled technologies. In line with Hondo (2005), Weisser (2007) conducted similar GHG emission assessment through LCA for different generation technologies along with carbon capture and storage and energy storage systems. Sovacool (2008) assessed GHG emissions from nuclear power plants. On the other hand, emissions from hydro and wind power generation were investigated and compared with other renewable and non-renewable generation technologies by Raadal et al., (2011). Two recent studies accounted electricity generation and related GHG emissions from municipal solid waste (MSW) in Macau, China and Iran (Q. Song et al., 2018; Rajaeifar et al., 2017). Li et al., (2016) and Ding et al., (2013) used the LCA approach to consider the contribution of synthetic natural gas (SNG) as a source of electricity generation towards possible carbon cuts in China.

The LCA has also been used to investigate emissions in renewable generation systems. For instance, potential solar PV deployment and associated GHG emissions reduction opportunities have been assessed in Peru (Bazán et al., 2018). Life cycle GHG emissions from on and off-shore wind turbines were estimated in Denmark (Sacchi et al., 2019). Briones Hidrovo et al., (2017) investigated the GHG emissions from two types of hydro reservoir, namely dam and run-of-river, and found that the latter is better with respect to GHG emissions if a full life cycle is accounted for. However, the results might vary due to various uncertainties associated with the reservoirs (Kumar et al., 2016). A recent study has investigated GHG emissions from 12 hydropower reservoirs in China and found that these systems emit more GHGs than the global estimated emissions for hydroelectricity generation (Kumar et al., 2019). Similar studies were also conducted for hydro power systems in India and the USA (Kumar et al., 2018; Song et al., 2018; Kumar and Sharma, 2016a; Kumar and Sharma, 2016b).

Other studies have used the LCA method in different contexts, including assessing emissions from electricity consumption (To and Lee, 2017), GHG emissions as a function of site condition (Reimers et al., 2014), emissions reduction through CCS technologies (Schreiber et al., 2012), and assessment of GHG emissions from electricity trading (Amor et al., 2011).

In view of all the studies mentioned so far, it is evident that the LCA approach has been widely used in the literature to report GHG emissions in a number of applications to electricity systems. Differing from these, some studies used well-to-wheel, well-to-wire, and well-to-meter methodologies in conjunction with LCA approach to assess GHG emissions (Moro and Lonza, 2017; Woo et al., 2017; Raj et al., 2016; Ou et al., 2011).

In terms of review studies, most of the studies focused on a particular generation technology or area, and then compared variations in GHG emissions using LCA as the method of assessment. These included electricity and heat generation from renewable energy technologies (Amponsah et al., 2014), electricity generation from renewable and fossil fuel technologies (Turconi et al., 2013), emissions from coal-fired electricity generation (Whitaker et al., 2012), emissions due to grid electricity consumption (Soimakallio et al., 2011), and emissions associated with nuclear power plants (Sovacool, 2008).

4.3 Marginal emissions approach

Marginal emissions refer to the GHG emissions that occur in electricity generation systems as a result of an additional unit of generation. For example, gas-fired power plants are often used to supply peaks in demand, and the amounts of GHGs that would be emitted due to an extra unit of generation is referred to as marginal emissions. Marginal emissions assessment explores the relationship between changes in system demand and associated GHG emissions, and this is measured by marginal carbon intensity (generally in kgCO_2-e/kWh). Marginal emissions accounting can be considered on an annual, seasonal, monthly or even hourly basis (Farhat and Ugursal, 2010; Gordon and Fung, 2009; Hitchin and Pout, 2002). Marginal carbon intensity can be defined (Rudkevich, 2009) as-

$$MCI(t) = \frac{\Delta CI(t)}{\Delta D(t)} \tag{3}$$

Where:
MCI: Marginal carbon intensity at time t.
$\Delta CI(t)$: Change in carbon intensity at time t.
$\Delta D(t)$: Change in the electricity demand at time t.

Numerous studies have investigated GHG emissions from electricity generation systems using a marginal emissions assessment method (Thomson et al., 2017; Howard et al., 2017; Thomson et al., 2017; McKenna et al., 2016; Olkkonen and Syri, 2016; Zhou et al., 2015; Graff Zivin et al., 2014; Kim and Rahimi, 2014; Hawkes, 2014; Hawkes, 2010; Ruiz and Rudkevich, 2010). A number of studies have used the marginal emissions assessment approach to assess future GHG emissions scenarios from the electricity sector. Howard et al. (2017), for instance, assessed future GHG emissions reduction potential for New York City for different generation scenarios; Kim and Rahimi (2014) found that an increase in plug-in electric vehicles in the city of Los Angeles due to current ‘time-of-use’ pricing would result in greater GHG emissions (average marginal emissions) than current levels; a similar result was also obtained for California (McCarthy and Yang, 2010). Thomas (2012), in contrast, estimated the change in GHG emissions due to increases in the number of electric vehicles (EV) in the USA and found that battery EV will produce more GHG emissions than gasoline hybrid EV. In a similar fashion, in Portugal, the EV uptake and associated GHG emissions in the near future was estimated by Garcia and Freire (2016) and found similar results to the USA, that is, an increase of GHG emissions. Apart from these, Carson and Novan (2013) estimated the peak and off-peak time marginal GHG emissions rate for the electricity sector from an economic point of view in Texas, USA.

In the UK electricity system, Thomson et al. (2017) investigated marginal emissions change due to changes in the total wind power in relation to the change in total system load, and found that increasing wind power was an effective option for GHG emissions reduction from the electricity sector. Structural change in the power systems and associated impacts on emissions was explored through long-run marginal emissions factor by Hawkes (2014). In an earlier work, Hawkes (2010) used this marginal emissions factor to estimate marginal emissions from UK electricity systems.

Collectively, these studies outline the critical role of marginal emissions approach in assessing emissions in the electricity sector all over the world. However, emissions taken into account are at the margins, which is the result of generation changes in the electricity system at the margins due to increases or decreases in electricity demand at a particular time. On the other hand, comparing marginal and average emissions factors revealed that the average emission factor misestimates the emissions that can be avoided from an intervention (Siler-Evans et al., 2012).

4.4 Index decomposition analysis approach

Divisia decomposition of CO_2 intensity (Shrestha and Timilsina, 1996) or index decomposition analysis (IDA) is another GHG emissions analysis approach used in the electricity sector (Xu and Ang, 2013; Ang et al., 2009). In this approach, change in carbon intensity in the electricity sector is decomposed into three components, namely fuel intensity effect, generation mix effect, and fuel quality effect, as shown in Eq. (4) (Shrestha and Timilsina, 1996). Logarithmic mean divisia (LMDI) is another form of IDA proposed by Ang (2004).

Detail mathematical calculation for IDA (i.e. divisia decomposition) can be found in (Shrestha and Timilsina, 1996). In general, IDA can be represented mathematically as-

$$\Delta CI = \Delta FI + \Delta G + \Delta FQ \tag{4}$$

Where:

ΔCI: Change in carbon intensity (in $kgCO_2/kWh$).

ΔFI: Change in fuel intensities.

ΔG: Change in generation mix.

ΔFQ: Change in fuel qualities.

Several studies have used the IDA approach to compare GHG emissions from the electricity sector. For example Ang and Su (2016) estimated the change in aggregated carbon intensity (the level of carbon dioxide emissions for each unit of electricity produced) in the electricity production sector for 124 countries (Ang and Su, 2016). IDA was also used to investigate the drivers of aggregate carbon intensity in ten ASEAN (Association of Southeast Asian Nations) member countries (Ang and Goh, 2016). Many other studies also used this approach to investigate electricity sector emissions (Peng and Tao, 2018; Liu et al., 2017; Meng et al., 2017; Karmellos et al., 2016; Yan et al., 2016; Yang and Lin, 2016; Zhou et al., 2014; Zhang et al., 2013; Steenhof and Weber, 2011; Shrestha et al., 2009; Steenhof, 2007).

4.5 Pinch analysis approach

Pinch analysis has been used to support emissions reduction targeting and planning at a macro-level. Pinch analysis is an extended version of thermal and mass analysis, and a graphical approach (Tan and Foo, 2007). Although the analysis is graphical, it accounts absolute emissions of GHGs. Pinch analysis involves an interplay between electricity demand, supply and GHG emissions limit. This process is illustrated in Fig. 4 (Rokni, 2016). Based on related data availability such as the emission factor, electricity demand, supply, and emission limit this process involves two steps: (i) plotting of electricity cumulative curve (i.e., demand and supply curves) against cumulative GHG emissions; (ii) identification of carbon pinch point by adjusting the curves in relation to the emission limit that needs to be met (Jia et al., 2010).

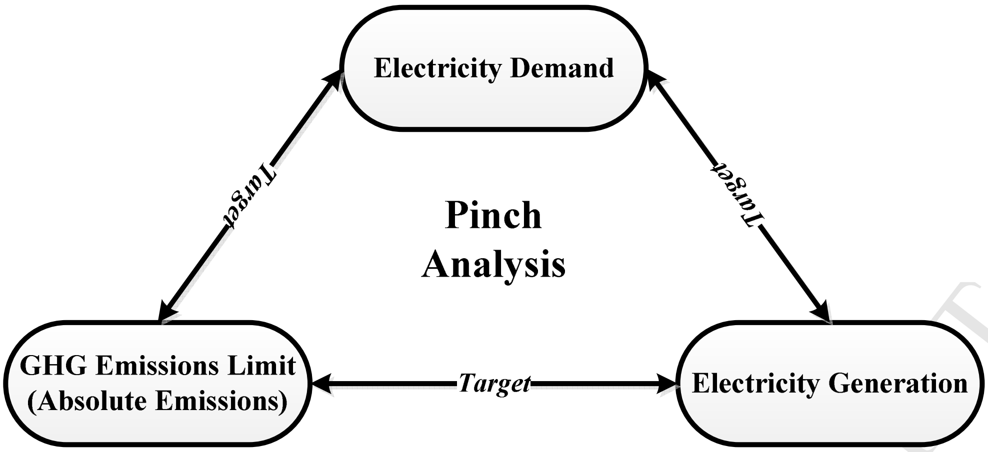

Fig. 4. Pinch analysis approach for electricity systems' emission accounting.

Previous studies have used pinch analysis to assess GHG emissions from the electricity sector (Walmsley et al., 2018; Atkins et al., 2010; Jia et al., 2010; Tan et al., 2009; Crilly and Zhelev, 2008; Tan and Foo, 2007). For instance, this approach has been applied to the New Zealand (Atkins et al., 2010) and Irish (Crilly and Zhelev, 2008) electricity sectors to identify possible GHG emissions reduction opportunities. The potential of CCS technology deployment in the electricity sector and associated GHG emissions abatement options were analysed through pinch analysis for the Philippine's electricity systems (Tan et al., 2009). In a recent study this approach has been used to assess the emissions and plan future electricity generation systems in the United Arab Emirates (Lim et al., 2018).

4.6 Time-varying carbon intensity approach

A time-varying carbon intensity approach considers temporal variations in GHG emissions [in gCO_2-e/kWh (t)] from electricity generation systems as a result of changes in the generation fuel mix. In any system involving a mix of renewable and fossil fuel generation, GHG emissions will vary significantly over time, and investigations at different time-scales (e.g. half-hourly, hourly, daily, weekly, monthly, seasonal, annual) can provide a detailed understanding of this variability. So far this assessment approach has been applied in just a few studies in different contexts (Khan et al., 2018; Khan, 2018a; Khan, 2018b; Kopsakangas-Savolainen et al., 2017; Roux et al., 2016; Gordon and Fung, 2009; MacCracken, 2006). Gordon and Fung (2009) applied this approach to the electricity systems of Ontario, Canada to explore potential options towards GHG emissions abatement through renewable generation. The study considered an hourly interval as the minimum to report

GHG emissions. In two very recent studies, a similar approach was also employed to identify emissions reduction opportunities for New Zealand's and Bangladesh's electricity generation systems (Khan et al., 2018; Khan, 2018a). Two other studies, in California, USA and Finland also used a time-varying assessment approach, but considered hourly consumption scenarios rather than generation (Kopsakangas-Savolainen et al., 2017; MacCracken, 2006). Roux et al. (2016) assessed the temporal variability of global warming potential per kWh for the electricity system in France. These studies used specific temporal time-blocks; however, much less attention has been paid to comparing GHG emissions at different time-scales or using it to contrast GHG emissions at peak and off-peak hours.

4.7 Other approaches

A few studies have used other approaches to estimate GHG emissions from the electricity sector. For instance, Santos et al. (2017) used a net emissions approach, investigating the difference between post-impoundment and pre-impoundment emissions from the hydro reservoirs. Structural decomposition analysis (SDA) along with aggregate intensity of CO_2 emissions, which is defined as CO_2 per unit of gross domestic product (GDP) has been used to investigate the relationship between energy (emissions) and GDP (Wang et al., 2017; Su and Ang, 2017). Soimakallio and Saikku (2012) considered production-based and consumption-based GHG emissions intensity in the OECD countries. It was found that consumption-based emission intensity accounting is more accurate for life cycle assessment than production-based emission intensity.

A study in Poland used total absolute emissions of different European countries and conducted cluster analysis based on a k-means algorithm to identify different clusters of countries that have similar emissions profiles (Kijewska and Bluszcz, 2016). Ji et al. (2016) proposed a 'Boundary-III' framework as an alternative GHG emissions accounting model, which considers electricity trading and accounts for direct and indirect emissions (Ji et al., 2016). Another estimation framework for GHG emissions accounting based on cross-border electricity trade within Europe has been introduced in (Zafirakis et al., 2015). A simple benchmarking approach was used in (Ang et al., 2011) to find potential global carbon emissions cut from the electricity sector. In an earlier study, Foo et al. (2008) presented a cascade analysis approach to consider energy planning that accounts emissions constraints.

5. Discussion and future scope

Together these studies provide important insights into the approaches that have been developed to date for GHG emissions accounting as applied to the electricity sector. A considerable amount of the literature is based on the LCA approach. While LCA is a comprehensive method, in that it considers all the stages associated with electricity generation (as shown in Fig. 3) to estimate GHG emissions, it has limitations. Life cycle data sourcing can be complex and produce uncertain data, and it is also difficult to deal with variations over time, so results obtained from the LCA approach need to be supported by other decision-making tools (Amponsah et al., 2014; Klöpffer, 2014). The same is true for the IDA approach, as it considers different decomposed steps of emissions changes.

Absolute emissions assessments are commonly used in national and international GHG emissions reporting, but this approach seems less effective than emission intensity when emissions are compared over time and compared between two countries with distinct sizes and economic conditions. A study on absolute versus intensity approaches to account GHG emissions was conducted jointly by the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR) at MIT. Empirical tests found "*...that intensity caps are preferable for a broad range of emission reduction commitments. This finding is robust for developing countries, but is more equivocal for developed economies*" (Wing et al., 2006).

Emission intensity can be assessed either as average emission intensity (or aggregate emission intensity) or marginal emission intensity, but these are defined differently and have different applications. Average emission intensity is defined as the ratio of total emissions from electricity generation to the total generation for a certain period of time (e.g., annual); whereas marginal emission intensity is the rate at which emissions would change as a consequence of small changes to the electricity demands at the margin. In general, marginal emission intensity is mostly used for economic analysis associated with GHG emissions (Carson and Novan, 2013). In contrast, average emissions intensity is used for policy-related decision making such as demand-side management (DSM) with respect to GHG emissions. However, it is a single-value quantity, which does not provide any temporal information about GHG emissions. The same is true for carbon emissions pinch analysis, which is a relatively complex graphical approach and does not provide any detailed insight about the temporal variability of emissions.

On the other hand, time-varying carbon intensity approaches account for temporal variations arising from changes in generation at all levels, for instance, from base load to peak load. A temporal carbon intensity approach could be an effective tool to assess GHG emissions from the electricity sector that would deal with both renewable and non-renewable generation as identified by Gordon and Fung (2009): "*Due to the divergence between when electricity can be generated and when it is required, an hourly GHG emission analysis is needed to truly understand the impact that these renewable technologies have on emissions*". However, far too little attention has been paid to this approach, in particular, emission variability during the hours of peak demand, which could potentially inform exploration of emissions reduction opportunities at peaks.

All the approaches that have been identified in this review are illustrated in Fig. 5. It can be seen that LCA is the only approach that has been extensively used for GHG emissions reporting in the published literature, which is about 37% of the publications reviewed. The next approach was absolute emissions, followed by IDA approaches with the percentages of 23% and 13%, respectively. Use of pinch analysis and other approaches were found to be 5% and 8%, respectively. On the other hand, in total, marginal and temporal emission assessment approaches were used in 15% of studies, of which the marginal approach was the maximum (12%) followed by the temporal approach (3%). Notably, marginal emissions deal with emissions from the electricity generation system at the margin; in contrast, the time-varying emissions approach considers emissions from the entire generation system.

The units of measure in different approaches were either in tonnes of CO_2-e (or kt CO_2-e or mt CO_2-e) or in gCO_2-e/kWh (or kg CO_2-e/kWh or tCO_2-e/MWh). Often both were used; for instance, in the LCA approach. Conversely, time-varying carbon intensity and marginal emissions were measured in gCO_2-e/kWh. Most of the approaches have considered the GHGs to be CO_2, CH_4, and N_2O. However, a few other studies have also taken into account other gases such as SO_2 and NO (Gordon and Fung, 2009). These are summarized in Fig. 6.

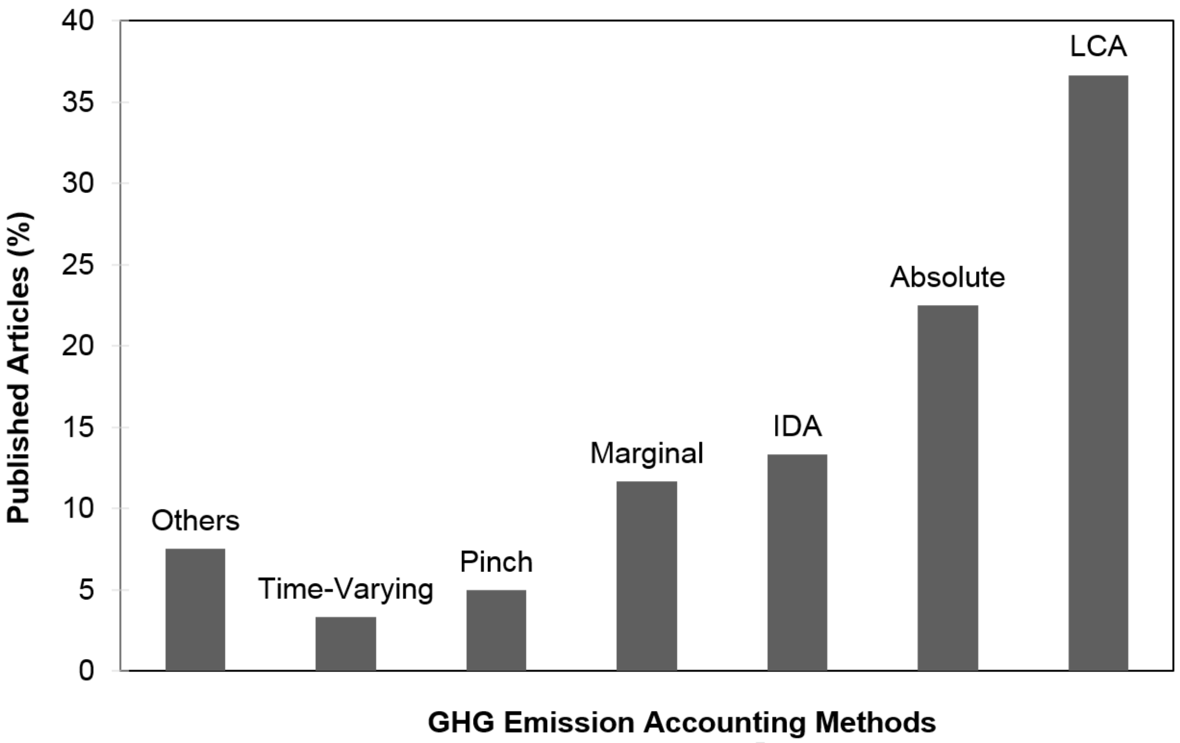

Fig. 5. Approaches used in assessing GHG emissions in the electricity sector.

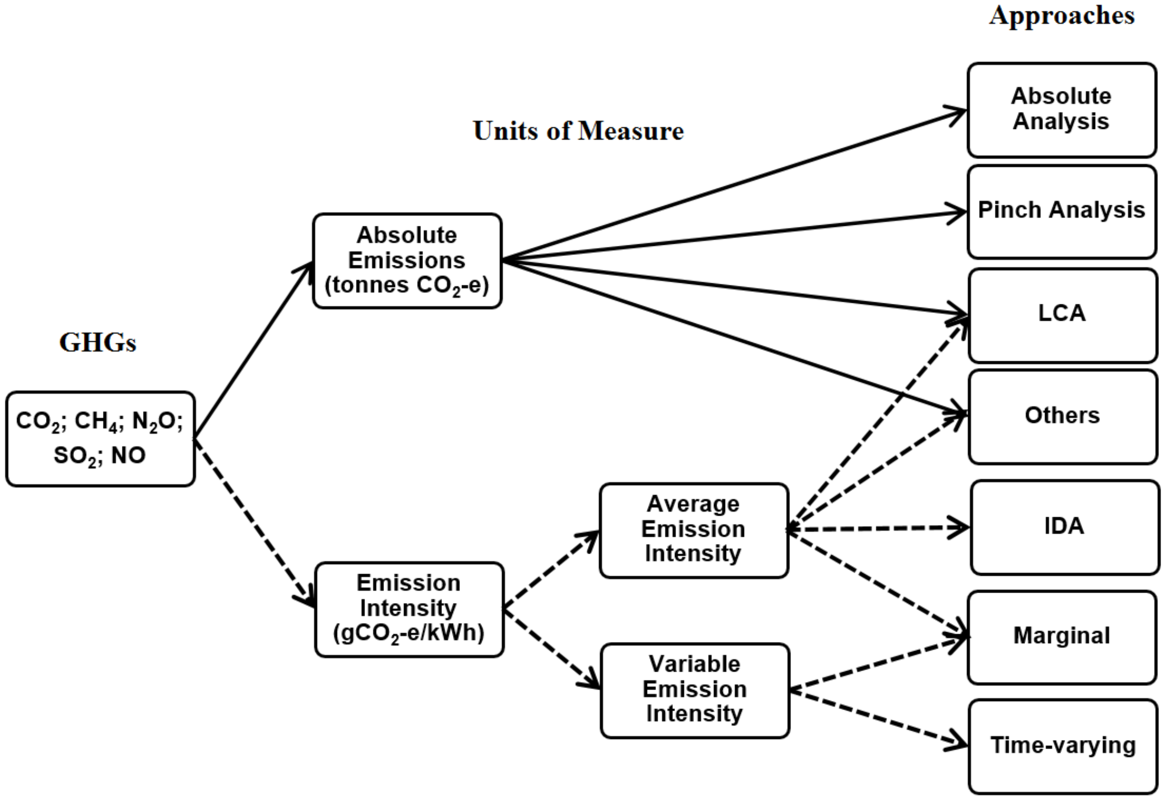

Fig. 6. GHGs, units of measure, and approaches found in the literature (Source: references mentioned in section 4).

Effective and accurate accounting of GHG emissions reveals a number of different opportunities for emissions control measures. Although LCA, IDA, absolute emissions and marginal emissions approaches are useful, they have certain limitations including the accountability of the time-varying nature of emissions intensity, which might be a significant matter for future electricity systems for a number of reasons, as follows.

(i) 100% Renewable generation: Globally, electricity generation systems are moving towards more renewable options to cope with negative climate change (Blakers et al., 2017). Nevertheless, 100% renewable electricity generation system might not be feasible due to technology limitations for a few more years (Heard et al., 2017). Electricity generation systems will thus have to deal with a considerable share of renewable and fossil fuelled generation, which would be challenging due to the intermittent nature of renewable generation (Olkkonen and Syri, 2016; APS, 2010). It was also found that- "*Ambitious plans of 30–50% renewable generation are, however, already raising concerns about the challenges of managing grids with a mix of renewable generation, with much higher levels of supply variability and geographically dispersed generation*" (Stephenson et al., 2018). Hydro generation, for example, varies from month to month; solar is diurnal, and wind strength varies from minute to minute. Fossil fuelled generation, in contrast, can be used as baseload generation or to meet peaks in demand, when there is a shortfall of renewable generations. Hence, the question is how to most effectively measure and mitigate the GHG emissions that have a time-varying nature due to the combination of fossil and non-fossil generation capacity in the generation fleet.

(ii) Generation fuel optimization: To ensure minimum GHG emissions from the generation fleet, including renewable and non-renewable capacities, it is essential to identify the optimum generation fuel mix that would ensure minimum emissions (Khan et al., 2017).

(iii) Demand-side management: It seems that time-varying carbon intensity assessment would be able to identify the carbon-intensive hours. This is important because if these hours coincide with peak demand hours, then demand-side management might be an effective option to reduce demand as well as GHG emissions. Subsequently, carbon abatement through on-site energy conservation measures and distributed renewable generations would be achievable through time-variable accounting of the carbon intensity. Furthermore, it would be a useful supporting tool to plan future grid expansion in relation to GHG emissions reduction (Khan, 2018a).

(iv) CCS/CCU technology evaluation: At present, CCS technologies have not been effectively implemented in electricity generation systems as one of the schemes of carbon abatement options due to the lack of efficient GHG emissions accounting and MRV rules. In a recent report, the IEA-GHG R&D programme reported that "….*there is genuine uncertainty about whether CCU technologies do actually deliver net GHG emission reductions, and whether they can be scaled up to create deep cuts in global GHG emissions over the medium term*" (IEA-GHG R&D, 2018). The time-varying carbon intensity assessment approach could possibly be an effective MRV tool to assess GHG emission cuts through CCU technology, but this needs further exploration.

(v) Carbon price: In a recent study, Chen et al. (2018) ascertain the need of a dynamic time-varying carbon pricing scheme as- "*Similar to electricity price, future carbon price changes daily or even hourly, while existing literature usually considers it as yearly constant value. Power generation companies will respond to the dynamic carbon price just like demand response to the electricity price. Consequently, dynamic carbon pricing mechanism is worth further research*." (Chen et al., 2018).

In addition, a recent report found that 90% of carbon emissions were not priced at the minimum level for 41 OECD and G20 countries and the electricity sector was found to be one source of these emissions (OECD, 2016; Mideksa and Kallbekken, 2014). Notably, those carbon pricing schemes were based on absolute emissions. Therefore, time-varying carbon price could be an effective option towards GHG emissions cuts through monetary action (Khan, 2018a). Overall, it seems that temporal carbon intensity assessment might be an effective option towards GHG emissions abatement, particularly from electricity generation system, but this requires further exploration.

Although emissions from electricity transmission and distribution were not extensively covered in this review, it is worthwhile mentioning that another potential fluorinated GHG, sulphur hexafluoride (SF_6) has been underestimated towards GHG emissions accounting in the electricity sector. It is important to account SF_6, as this gas is used in electrical transmission equipment (e.g., circuit breakers) (Zhang et al., 2017), which has GWP of 23500

(GHG Protocol, 2018), and the IPCC has also highlighted this gas in emissions accounting (US EPA, 2018).

6. Conclusion

A review of the electricity sector's GHG emissions accounting approaches has been conducted in this study. In particular, emissions from electricity generation was considered, however, emissions from transmission and distribution were also considered, where relevant. A total of 120 recent articles were found directly related to electricity and GHG emissions. A range of GHG emissions accounting approaches was identified, including life cycle assessment, absolute emissions analysis, index decomposition analysis, marginal emissions approach, pinch analysis, and the time-varying carbon intensity approach. Much of the published literature reviewed here paid particular attention to the life cycle assessment approach, with a 37% share, followed by absolute emissions and index decomposition analysis with the shares of 23% and 13%, respectively. Less attention has been paid to time-varying carbon intensity approach (3%).

Although the life cycle assessment approach was used predominantly in the literature in accounting GHG emissions from the electricity generation sector, it has limitations, such as data uncertainty. The same is true for index decomposition analysis. On the other hand, absolute emission and pinch analysis seem less useful when comparing emissions of different entities with different characteristics (e.g., economic conditions of a country). In addition, pinch analysis is a complex graphical approach. Overall, these approaches are unable to account temporal variability of GHG emissions on different scales. Apart from these, marginal and time-varying approaches are useful in accounting temporal variability of emissions. However, the marginal emission approach only accounts emissions at the margin of the generation system. In contrast, the time-varying approach is capable of accounting temporal variability of emissions over different time scales. Nevertheless, the time-varying approach is unable to account indirect emissions from renewable sources due to the unavailability of proper emission factors.

Since renewable integration in the electricity sector is becoming significant in order to ensure a global low-carbon future, time-variability of generation (from fossil fuels and renewables) and associated GHG emissions would be a common but challenging phenomenon for future electricity generation systems to deal with. Therefore, the time-variable carbon intensity approach in relation to GHG emissions accounting could make a potential contribution towards the monitoring, reporting, and verification process. Moreover, this approach would be able to explore demand-side management opportunities with respect to GHG emission reduction scopes at different time scales. However, further research is essential to explore this approach in detail.

In the light of this review, future research could explore the options of using time-varying carbon intensity analysis approach:

- To optimize the generation fuel mix (i.e. renewable and non-renewable) to maintain minimal emissions from electricity generation. In addition, this would help to plan future grid expansion by maintaining a low-carbon grid.
- To reduce GHG emissions during peak demand times through different demand response schemes.
- In assessing the performance of new CCS/CCU technology towards GHG emission reductions from the electricity sector.
- In exploring time-varying carbon prices schemes to ensure emission reduction from different entities including electricity generation systems.

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Highlights

- A review of available GHG emissions accounting methods in electricity systems.
- Explored the limitations and future research scope in GHG emissions accounting.
- Supports policymaking to select proper approach in accounting GHG emissions.

Declaration of Interest

Date: 8th Dec 2018

To
The Editor
Atmospheric Environment

Dear Editor,

I confirm that this work is original and has not been published elsewhere nor is it currently under consideration for publication elsewhere.

Conflict of interests: none.

In this paper, a scoping review of available GHG emissions accounting approaches has been conducted to explore the limitations and future research scopes in the field of electricity systems. Even though some review articles have been published on particular GHG emissions approaches (e.g. life cycle assessment), studies that investigated overall approaches have rarely been identified in the literature. This is significant because this review summarises the available approaches that have been applied in accounting GHG emissions in electricity systems and could be a good starting point towards further GHG emissions related research.

In addition, this review would be helpful for the policymakers to select proper approach in accounting GHG emissions from the electricity systems towards any new policymaking. Therefore, this paper should be of interest to readers in the areas of GHG control, sustainable development, electrical energy systems and networks, environment and climate change.

Please address all correspondence concerning this manuscript to me at ikr_ece@yahoo.com.
Thank you for your consideration of this manuscript.

Sincerely,

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