Quantifying Greenhouse Gas Emissions: A Review of Models and Tools at the Precinct Scale

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ABSTRACT

Although urban areas cover only 3% of the earth's land surface, they are responsible for over 70% of greenhouse gas emissions (GHGE) from energy use. Cities are versatile, dynamic and complex. Therefore, implementations of low carbon initiatives at city scale are challenging and at times impractical. From the local administration perspective, the precinct scale represents a manageable operational scale for governance, urban planning and socio-technical innovations. There are various methods for quantification of GHGE at building, precinct, city and national scales, but few target the complexity and dynamics of the urban area, especially at the precinct scale. The aim of this paper is to identify a suitable quantification method for the precinct scale. The method should be able to determine the changes in GHGE due to implementations of low carbon policies and other strategies. This paper reviews the available methods for quantification of GHGE and highlights their challenges and limitations. Since urban areas need a system thinking approach, this review outlines how the methods analyse complex systems, such as System Dynamics (SD).

Keywords: *quantification of GHG emissions, low carbon, precinct*

1. INTRODUCTION

Urban areas, such as cities, are responsible for a significant portion of greenhouse gas emissions (GHGE) and at the same time, are vulnerable to climate change impacts. Urban energy systems are resource intensive and fossil fuel dependent, contributing to the high concentrations of GHGE released from urban areas. This situation could be exacerbated if the proportion of the global population living in urban areas increases from 50% to 66% as predicted for 2050 (UN 2015). To sustain this urban population growth while reducing GHGE and city's vulnerability, urban areas need to transition from carbon intensive to low carbon practices.

Therefore, measurement and quantification of GHGE in urban areas are vital to develop mitigation, adaptation strategies and to achieve GHGE reduction targets. Quantification methods should be able to capture the changes of GHGE from different low carbon policies and other strategies. These methods have been developed for different purposes such as monitoring, reporting, planning, decision-making, and analysis of land-atmosphere carbon exchange. These methods distinctly define spatial and temporal system boundaries, making their comparison a challenging task. Furthermore, most of the methods, such as rating tools and accounting methods, fail to capture the dynamics and complexities inherently present in urban areas.

There is a need for methods to capture these complexities and dynamics. Therefore, the aim of this review is to identify the most appropriate method to quantify the changes of GHGE from low carbon initiatives in urban precincts. To do so both academic and grey literature in quantification of GHGE were reviewed to identify 1) the techniques for quantification of GHGE in urban areas 2) explain challenges and limitations, and 3) propose a suitable approach to quantify changes of GHGE in a precinct scale when testing low carbon strategies. Since energy systems are an essential part of an urban area and significant generators of direct and indirect GHGE, contribution from review articles on energy methods, tools and models are taken into account in this paper.

Section 2 presents a general overview of the techniques used for quantification of GHGE in urban areas. Section 3 discusses challenges and limitations of current techniques and explains why those in the complex system realm are the most appropriate for the purpose of quantifying GHGE when analysing low carbon strategies at the precinct scale.

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2. QUANTIFICATION OF GHGE IN URBAN AREAS

2.1 Complexity, dynamics and scale considerations

Cities have extensive mixed land use areas with distinct characteristics and infrastructures of provision, governed by different authorities and accommodate diverse occupant profiles. Cities and, in general, urban areas should be regarded as complex systems. They are also dynamic. Their dynamics link to different rates of changes of their subsystems, for instance slow land use change compared to fast transport of goods (Simmonds et al. 2013).

These intertwined relationships and different rates of change clearly intensify the implementation challenges for low carbon strategies at a country or city scale. A precinct or neighbourhood, however, represents a more manageable scale (Rauland 2013). In precincts, likeminded communities might easily engage and collaborate with initiatives. Also, a precinct represents an operational unit where low carbon strategies can be developed accordingly to the site characteristics and requirements, taking into account the physical and socio-economic relationships even outside its immediate boundaries. This review investigates different types of quantification of GHGE but focus the analysis at the precinct scale since the idea of targeting an intermediate scale, between the city and the individual building, to implement low carbon initiatives.

2.2 Methods

Quantification methods are developed for reporting, rating, decision-making, design and urban planning, and policy making purposes. In general, urban GHGE quantification methods can be classified as top down, bottom-up or hybrid (Ou 2012; van Vuuren et al. 2009). The characteristics and limitations of these three main approaches have been reviewed before by other authors. This review investigates at more specific models and tools (e.g. bottom-up building stocks).

Different international protocols and standards, developed for the quantification of GHGE since the late 1980's, follow a top-down approach, using econometric models and accounting methods at macro scales. The top-down quantification of GHGE using econometric models emphasizes the analysis on market processes by studying the economy of a country as a whole. This type of approach overlooks sociotechnical detail, it is static and uses highly aggregated historical data.

On the other hand, bottom-up methods look at individual technologies or energy consumption in houses and extrapolate them to the regional or national scale. They use statistical or engineering methods. While these methods capture sociotechnical and other details (e.g. building physics), they overlook their relationship with the economy. Although both methods, top-down and bottom-up, have different applicability, they can be combined to take a hybrid approach.

There are more comprehensive models that take the sustainability triple bottom line perspective, assessing not only GHGE but also other environmental and socio-economic impacts. They use geographical information systems (GIS), optimization algorithms and scenario analysis. These types of models are mostly used by the design and urban planning sectors for decision-making at early stages of a project.

The typical spatial scales used for quantification are building (micro), neighbourhood (local) or city/country (macro) scales. At micro scale (building), the most common and accepted approach for environmental impacts is Life Cycle Assessment (LCA). LCAs can include energy and/or greenhouse gas (GHG) analysis, life cycle eco-footprint, and integrated criteria weighting as part of their methodology (Iwaro et al. 2014). This method has contributed significantly to the analysis of impacts in the built environment.

LCA has also been developed in recent years for local scales. There is sound research on residential configurations and related GHGE (Crawford and Fuller 2011), as well as preliminary work on urban-building life cycle analysis and interactions (Stephan 2013). LCA can incorporate scenario analysis and complement the assessment with GIS techniques. Lotteau et al. (2015) presented a comprehensive review of LCA for local scale. The authors proposed a common definition of a Functional Unit (FU) to improve comparability and analysis. They also claim for a clear contextualization of the neighbourhood and a clear definition of temporal scales to improve decision making.

Another key approach for local scales is the bottom-up building stock models reviewed by Kavgic et al. (2010), where building physics and empirical data can be combined to estimate the energy consumption and related GHGE.

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The issues including lack of data transparency, data availability and uncertainty related to how society consumes energy and reacts to changes from energy policies were identified.

Local and macro (City) scales can be also analysed with the urban metabolism (UM) methodology (Codoban and Kennedy 2008; Kellett et al. 2013; Kennedy 2011). UM is applied as an accounting method mainly looking at mass balance and "emergy" of a system. Pincetl et al. (2012) presented how UM can be expanded to allow a more comprehensive and integrative assessment by evaluating electricity, water and solid waste flows plus a LCA of the related infrastructure.

Other accounting methods at local and macro scales are: carbon accounting with input-output models (Wiedmann 2009), GHG footprint, GHG inventory analysis (Chester et al. 2014) and protocols, i.e. The Global Protocol for Community Scale (WRI 2014). These accounting methods of material and energy flows are useful to identify mismatches between demand and supply but they take a static approach.

Allegrini et al. (2015) present a review for the design and planning of district-scale energy systems, highlighting the need for simpler decision making tools, holistic approaches and the opportunity to integrate different models. For decision making and urban planning at this scale, the use of urban simulation models (Rager et al. 2013; Waddell 2002), survey data analysis (Newman and Kenworthy 1989), and material flow (Goldstein et al. 2013), are the most common methods.

All methods described so far are still considering urban areas as static systems. System thinking (ST) is potentially the most convenient perspective that addresses urban areas as complex systems as it is focused on the entire system as a whole, while also accounting for its components and subsystems and how they interact with each other (Waltner-Toews et al. 2008).

However, ST ignores the main relationships with the outside boundary of the system under study. Methods for modelling complex systems following the ST perspective such as System Dynamics (SD) (Feng 2013; Wang et al. 2012), Cellular Automata (CA), and Agent Based Modelling (ABM) (Aschwanden et al. 2012; Natarajan et al. 2011) have the potential to better capture the characteristic features of urban areas.

2.3 Models and tools

A selection of few representative tools is described in this subsection. In general, models and tools for quantification of GHGE build upon one or more methods described before. Rauland (2013) presented a review of typical tools used at precinct scale, including the designing tools eTool and CCap. These tools include quantification of GHGE among other performance metrics for decision making at design stages, but they do not take into account all the subsystems present within an urban ecosystem. The review highlighted the need for a precinct scale GHGE framework using LCA to calculate embodied and operational emissions.

Alternatively, the Australian Stocks and Flows Framework (ASFF) was developed by CSIRO to deal with the processes that support economic and social activities and describe them in dynamic and in physical terms (Turner 2011). ASFF describes the biophysical Australian environment combining different methods such as LCA, and metabolism-based such as mass-flow analysis. All methods are linked as calculators using nationwide databases and simulation processes that complement the analysis tool using what-if scenarios. It is a powerful and comprehensive framework for national and regional scales, but it lacks the finer data resolution needed at the precinct scale.

The urban planning tool, Integrated Resource Management (IRM), is a complex excel spreadsheet (Birch et al. 2013) used as a guidance tool for sustainable urban design and planning. It offers a common framework where urban designers and technical teams can design processes to capture key performance indicators (Page et al. 2008), but they do not capture the urban ecosystem dynamics.

MUtopia is a simulation tool for engineering sustainable systems in local scale. This platform integrates areas such as energy, water supply, waste and transport through spatial data infrastructure. The platform allows testing different scenarios including impacts in GHGE from distributed infrastructure of water or energy supply (Bishop et al. 2008). However, the results are limited due to the assumptions made to simplify the models (Ngo et al. 2014).

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UrbanSim is a simulation software tool for urban planning. It assesses the impacts of infrastructure within a metropolitan area by integrating the interactions and approximating the dynamics between land use, transportation, the economy and the environment. UrbanSim is the only tool within this selection that uses ABM, a method from the complex systems realm. It is a powerful open source simulation tool for local scale, but it lacks the integration of other infrastructures of service such as water, waste, and electricity.

3. DISCUSSION

This section describes the limitations and challenges of the methods and tools reviewed, describing a suitable GHGE quantification approach at the precinct scale.

3.1. Limitations and challenges

All the methods reviewed define different system boundaries, functional units, spatial and temporal scales for analysis, making their comparison challenging. Methods, such as carbon accounting, usually follow a top-down approach, and long temporal and broad spatial scales hindering the identification of potential opportunities to reduce GHGE at the precinct scale. Moreover, reporting and accounting methods are static and do not have the capacity to test future scenarios, diminishing their ability to analyse different policies or interventions.

Most of the methods limit their quantification to operational impacts, while there is a need for tools able to assess operational and embodied impacts simultaneously (Newton 2013). Linked to the need for embodied impact data, is the need for finer data resolution in order to capture the complexity of urban ecosystems. However, balancing complexity and computing costs with accuracy represents a challenging task. Nevertheless, the most important limitation for any method is the availability of representative, complete and consistent data of the urban ecosystem under study.

Also, methods should include the dynamics related to different rates of change of subsystems, which increase the system complexity and uncertainty. Uncertainty analysis should be performed and used to visualise the evolution of different parameters of an urban area, especially when analysing transitions to low carbon futures.

3.2. Appropriate method

Embedded systems and processes in precincts, such as the energy system and related GHGE, have all the main characteristics of complex systems, including agents, networks, path-dependency, emergence and co-evolution (Bale et al. 2015). Therefore, complex systems approaches may better represent transitions to low carbon futures than carbon accounting methods. The sustainability transition modelling community uses ABM or SD to simulate and explore socio-technical transitions in the built environment (Li et al. 2015), mostly assessing the energy area and related GHGE.

ABM is well suited to represent a high degree of heterogeneity across entities assuming there is perfect information about the interaction network. However, this level of detail comes at a high computational cost that limits the use of the model for sensitivity analysis for policy making, increases the complexity of understanding the causes of the results (Rahmandad 2008) and relies heavily on data accessibility which in most real world scenarios is unavailable.

In contrast, SD relaxes the level of detail of the entities through aggregation and lends itself to fast scenario analysis, at the cost of losing track of possible metrics. The design choices when modelling with SD should be made to capture the main metrics accurately, ignoring only the ones that are less important for policy making. Also, Discrete Event (DE) modelling can be easily integrated along with SD to model micro level details that do not involve continuous processes, such as traffic flow, and commuting patterns (Borshchev 2004; Zeigler 2000).

The ST perspective, which analyses the whole system, its subsystems and their interactions, is a valid approach to describe complex systems. However, ST ignores the relationships with the outside boundary of the main urban system under study. Therefore, models driven by the ST approach should be expanded to approximate the main relationships of the system with its outside boundary, especially the ones linked to changes of GHGE.

In terms of tools, ASFF and UrbanSim show the potential for coupling modelling methods, a valid option for assessing possible futures in urban ecosystems (Sheridan et al. 2016). Any successful method for quantification of GHGE changes should include features such as coupled modelling and different time delays (e.g. Urbansim), to better represent the complexity and dynamics of urban ecosystems. Furthermore, suitable methods should be flexible to include data from low carbon initiatives already applied in other contexts as demonstration projects. This data can be used as inputs of the model to examine GHGE reductions from distributed infrastructures, or other technological scenario adoptions (Mohareb and Kennedy 2014).

Moreover, future transitions to low carbon precincts are uncertain in nature, therefore the use of exploratory modelling and analysis represent an opportunity to discover what could happen (Maier et al. 2016), even if the scenarios are generated externally or strategically for decision making (Börjeson et al. 2006).

4. CONCLUSION

The methods for quantification of GHGE in urban ecosystems were reviewed. It highlighted the importance of targeting urban areas at the precinct scale when implementing low carbon initiatives; therefore the review includes quantification models and tools at this specific scale. It summarises the limitations and challenges of different methods and suggests that future work on quantification of urban GHGE should use models with the underlying methodologies from complex systems. The analysis of urban areas, regarded as urban ecosystems, could benefit from the systems thinking approach with a multidisciplinary perspective when quantifying GHGE changes. It is also recommended the use of exploratory modelling and analysis. This would assist representing different future pathways of low carbon transitions and accounting with the inherent system uncertainties.

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