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Selecting climate change mitigation strategies in urban areas through life cycle perspectives

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ABSTRACT

Urban governments globally have generated climate change mitigation plans in recent decades. With greenhouse gases (GHG) being emitted from far-ranging anthropogenic sources, selecting mitigation alternatives from a portfolio of options can be highly challenging, particularly when capital budgets and life cycle costs are considered. This research combines life cycle assessment (LCA), life cycle cost accounting (LCCA), and mathematical formulation methods to select ideal alternatives for a case study city. We utilize LCA and LCCA to determine the environmental and economic costs associated with 15 different GHG emission abatement alternatives in four different infrastructure systems: lighting, transportation, buildings, and energy. These abatement alternatives are also assessed for high, medium, and low emission reduction scenarios. For this problem we propose two mathematical formulations to apply to the LCA and LCCA results. The first mathematical formulation is for a single-phase implementation of all selected solution design alternatives; the second mathematical formulation applies to the implementation of alternatives done in three phases. The modeling results reveal the selection differences that occur when capital budgets are varied for both single and multi-phase planning. This unique approach to urban GHG abatement planning can effectively aid policy makers in efficiently selecting best practices in climate change mitigation when balancing environmental and economic perspectives.

1. Introduction

Urban governments worldwide are seeking to reduce greenhouse gas (GHG) emissions through a portfolio of strategies. Although specific quantities for climate change impacts from urban areas vary significantly (Dodman, 2009; Hoornweg et al., 2011), cities represent a major portion of global emissions, and trends in urbanization and urban sprawl can complicate impact mitigation efforts (Hoornweg et al., 2011; Ala-Mantila et al., 2013). Many cities have adopted climate action plans globally (NYCDEP, 2008; City of Munich Dept of health and environment, 2010; TMG, 2007; CCSF, 2013; City of Sydney, 2013; City of Portland, 2015), but implementation and execution of GHG emission reduction can be challenging when economic and social considerations are incorporated into planning.

In the absence of GHG emission pricing standards ($/tonne $CO_{2(eq)}$), evaluating the cost-effectiveness of GHG emission abatement alternatives is critical. When planners must allocate economic budgets across a range of emission reduction alternatives, having full knowledge of life cycle costs and abatement potential is crucial. These alternatives can exist in many different forms: technologies (e.g., renewable energy systems, low-emission vehicles, energy-efficient lighting), management practices (e.g., leak management in water distribution), and consumer practices (e.g., resource conservation). Efficiently navigating many alternatives adds another level of complexity to the problem when evaluating abatement potentials and associated costs. Valuing GHG emission abatement alternatives through economic tradeoffs is powerful means of identifying “low-hanging fruit” for emission reductions. Recent research has assessed these economic and environmental trade-offs in transportation systems (Fernández-Sánchez and Berzosa, 2015; Gosse and Clarens, 2013; Reger et al., 2014; Wang et al., 2014), renewable energy supply chains (Lam et al., 2010; Hendrickson et al., 2013; Cucchiella and D'Adamo, 2013; Wolfram et al., 2016), and water distribution systems (Wu et al., 2012, 2013; Blinco et al., 2016).

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Previous research (McKinsey & Co, 2009; Lutsey and Sperling, 2009; Stokes et al., 2014) has applied some of these methodologies to quantify and visualize the economic and GHG emission abatement potential of different mitigation strategies, summarized by environmental abatement costs (\$/tonne $CO_{2(eq)}$ abated), but does not extend to applications of decision-making methodologies. Our proposed research in this study creates a unique approach by combining life cycle methodologies and integer programming models with the objective of selecting best practices among alternatives. In the assessment of urban GHG abatement alternatives, we used life cycle assessment (LCA) and life cycle cost accounting (LCCA) to determine the emission reduction potential, capital costs, and life cycle costs of different emission reduction alternatives. These alternatives represent a wide range of infrastructure systems found in urban environments: transportation, energy systems, drinking water distribution, and buildings. We then apply an integer programming model to determine the most desirable alternatives under various scenarios. Using these mathematical models to address complex environmental and economic problems enables policy makers to efficiently determine optimal outcomes (Gonzalez et al., 2015). This methodology is applied to a case study city to create potential real-world results.

1.1. Related decision-making literature

Previous related literature has used various multi-criteria decision analysis (MDA) methods to select technologies and alternatives in environmental mitigation. These methods include analytical hierarchical process (AHP), analytical network process (ANP), technique for order preference by similarity to an ideal solution (TOPSIS), VIseKriterijumska Optimizacija I Kompromisno Resenje, i.e., multicriteria optimization and compromise solution (VIKOR), and others.

Recently, fuzzy versions of these methods have been more widely used (e.g., fuzzy AHP, fuzzy ANP, fuzzy TOPSIS, and fuzzy VIKOR). Fuzzy techniques have been proposed because some values of alternatives per criteria (but rarely all of them) were not crisp numbers. Fuzzy numbers can be used to adequately address noncrisp numbers. For example, let us suppose that we have three alternatives and three criteria. Let us suppose that for criteria 1 and 2 alternatives have crisp values and for criteria 3 we have triangular fuzzy numbers. Matrix A, whose elements represent values of alternatives per criteria, can be given in the following way:

$$A = \begin{bmatrix} 120 & 50 & (15,20,30) \\ 130 & 45 & (17,22,27) \\ 150 & 47 & (20,23,25) \end{bmatrix}$$

This problem cannot be solved by standard versions of MDA techniques, but it can be done by their fuzzy versions (for example, fuzzy TOPSIS).

Kabir and Sumi (2014) proposed an integrated fuzzy AHP and preference ranking organization method for enrichment evaluations (PROMETHEE) for a power substation location selection problem. Guerrero-Baena et al. (2015) considered the problem of selecting the best management system from the set of possible alternatives. The authors proposed a decision-making approach based on ANP in order to evaluate and prioritize environment management system alternatives. To identify the key factors and criteria for carbon management, Liou (2015) applied decision-making trial evaluation laboratory (DEMATEL). This method was used to make a relationship among an evaluation system and the ANP method. Deveci et al. (2015) considered the problem of choosing the best location for CO_2 storage. The authors compared results obtained by three fuzzy-based multi-criteria decision-making methods (fuzzy TOPSIS, fuzzy ELimination and Choice Expressing the REality (ELECTRE I) and fuzzy VIKOR). Wang and Poh (2014), and Govindan et al. (2015) also provided a broader review of the related literature.

In this paper we considered the problem of selecting multiple mitigation alternatives to create a portfolio of abatement solutions. In our modeling, GHG mitigation alternatives were selected to minimize total life cycle cost. The model also took into consideration a capital budget that could not be exceeded in implementation of alternatives. In addition, target annual abatement for each considered goal (i.e., negative ecological effect) had to be satisfied. For this problem we proposed two integer programming mathematical formulations: one for the case with one phase, and the second for multiple phases.

These two models address the temporal variations that exist in climate change mitigation planning. To the best of our knowledge similar approaches have not been found in the related literature. We proposed integer programming models because some additional constraints (such as available budget, target annual abatement for each goal, more phases) must be taken into consideration. These constraints cannot be incorporated into MDA models. With MDA techniques we first must rank abatement alternatives, and after that, we must apply another technique to select alternatives for each planning phase in a way that satisfies all defined constraints. With proposed integer programming models a final solution can be found immediately. Therefore, we believe that integer programming models are suitable, the most efficient, and the most useful approaches for the considered problem.

2. Methodology

2.1. Life cycle economic and environmental analysis of case study

This study used assumptions and data sources from the City and County of San Francisco. San Francisco has aggressive mitigation goals, motivated by both state and local ordinances. These goals include annual emission reductions below 1990 levels of 25% by 2017, 40% by 2025, and 80% by 2050 (CCSF, 2013). To achieve these abatement goals over the next decades, city and county leadership must efficiently select mitigation alternatives. While San Francisco's GHG emission mitigation goals are aggressive for a developed country and particularly for the United States, the region has similar trends and characteristics that many developed cities also experience, such as rapid urbanization and an increasing population density. San Francisco's population was 840,000 in 2013, an increase of 4% over the last 5 years (U.S. Census Bureau, 2013). San Francisco is also one of the most densely populated cities in the U.S., with almost 7000 people/km^2 (Governing, 2013).

We used LCCA in determining the capital and operational costs associated with a selection of abatement alternatives. The energy and GHG emission assessments used LCA in evaluating the design alternatives. LCA is a holistic method of quantifying the associated environmental impacts of products and processes. LCA allows researchers to track inputs and outputs at all stages of a product/process's lifetime: from raw materials extraction to disposal. Users of this method can readily identify the major contributors to a given environmental impact for mitigation. This study specifically uses both process-based and economic input–output (EIO-LCA) to create a hybrid LCA.

The study adapted the approaches and data sources used in (Stokes et al., 2014) to San Francisco-specific characteristics to generate GHG abatement alternatives for analysis. Table 1 details the data sources, assumptions, and methods used in assessing the abatement alternatives.

All alternatives were assessed over a 20-year period (2015–2035). We estimated GHG emissions from electricity (g $CO_{2(eq)}$/kWh) based