Energy Policy 121 (2018) 92–100

Contents lists available at ScienceDirect

Energy Policy

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

A study on probabilistic social cost–benefit analysis to introduce high-efficiency motors into subway station ventilation

Junlong Quan[a], Se-Heon Kim[a], Ju-Hyung Kim[b,*]

[a] Department of Architectural Engineering, Hanyang University, #611-2 Engineering Science & Technology B/D, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

[b] Department of Architectural Engineering, Hanyang University, #611-1 Engineering Science & Technology B/D, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

A R T I C L E I N F O

Keywords:
Subway station ventilation
Variable speed ventilation
High-efficiency motors
Probabilistic social cost–benefit analysis
Monte Carlo simulation
Life cycle cost

A B S T R A C T

As a solution to enhance the air quality for public health while reducing energy consumption, introduction of high efficiency motors with inverters enabling variable speed operation of subway station ventilation systems has been proposed. However, as the initial costs for these alternative systems are around eight times more than those for conventional fixed speed systems, a comprehensive feasibility analysis should be conducted. Previous analyses focused on economic benefits based on predetermined loads for ventilation. As such, the various social benefits that are dynamically determined according to energy saving resulting from variable speed operation could not be determined. This research presents a probabilistic social cost-benefit analysis model. The ventilation systems' operational loads are mainly affected by particulate matter concentrations; these can be predicted through probabilistic simulation of previous weather data. The probabilistically analyzed energy saving influences the social benefits i.e. fuel reduction, carbon dioxide reduction, and air pollutant reduction. The proposed analysis model is validated with real world data obtained from the operation of underground subway station ventilation systems in which synchronous reluctance motors (SynRM), a type of high efficiency variable speed motor, and inverters are installed by the authors.

1. Introduction

In metropolitan areas with high populations, underground transportation systems operated with electricity have been regarded as solutions to relieve traffic congestion and air pollution (Kim et al., 2013). However, air pollutants generated from both inside and outside tend to be accumulated within underground stations due to having few open facades that would enable natural air flows. Air pollutants are mainly composed of particulate matters and carbon dioxide, which pose a threat to the health of passengers and subway staff (Kwon et al., 2010; Kim et al., 2013; Brauner et al., 2014; Han et al., 2014). Ventilation-introducing mechanical systems are likely able to maintain an adequate level of air quality by reducing air pollutants; the challenge is that the mechanical ventilation systems cannot be run as frequently as needed due to the associated energy costs. In general, this ventilation accounts for 14–35% of the total energy consumption required for station operation (Casals et al., 2014). This rate is anticipated to increase due to the growing interest in indoor air quality in public facilities.

High efficiency motors with inverters enabling variable speed operation have been suggested as an alternative to enhance the performance of ventilation systems without burdening energy costs (Aarniovuori, 2016). The ventilation loads can be optimized based on the dynamic need to control particulate matters concentration (Kim et al., 2015, 2016). Despite the ideal performance of variable speed ventilation systems, they require additional initial costs compared to fixed speed ventilation systems (Kwong et al., 2017). In general, the motor itself for the variable speed is around five times more expensive than that for the fixed speed. In addition, inverters should be installed to control motor revolving speed, resulting in overall initial costs around eight times higher than the conventional systems consisting of fixed speed motors. Despite these extra costs, the obvious benefits in terms of public health and other social benefits promote the need for a comprehensive cost-benefit analysis.

This paper presents a new approach for exploring the feasibility of introducing alternative systems for environmental control in public facilities by means of probabilistic social cost-benefit analysis. To optimize operations, systems that can acquire real time data from advanced sensors with controls that use decision making algorithms are required. However, in the real-world situation, there are various technical aspects of this kind of system that should be examined to assess

* Corresponding author.
E-mail addresses: Junryong1122@nate.com (J. Quan), noname-0001@hanmail.net (S.-H. Kim), Kcr97jhk@hanyang.ac.kr (J.-H. Kim).

https://doi.org/10.1016/j.enpol.2018.06.007
Received 8 January 2018; Received in revised form 29 May 2018; Accepted 2 June 2018
0301-4215/

reliability. Furthermore, practical analysis methods, particularly for considering the dynamic aspects of ventilation loads, have to be developed to support decision making regarding the introduction of alternative systems. For instance, the economic analysis of previous studies has assumed predetermined systems loads and focused on direct benefits from energy saving and costs for initial implementation, maintenance, operation and demolition (Ozyogurtcu et al., 2011, 2014; Kwong et al., 2017). The analysis frame needs to be evolved to include the dynamic aspects of energy saving and the related social benefits. Fundamental principles are: 1) energy saving can be predicted by analyzing the pattern of the appearance of certain factors by means of probabilistic simulation of previous weather data and 2) social benefits in addition to direct energy savings exist and those are relatively determined by the energy saving. In public facilities, the social benefits are analyzed through simple historical data at the planning stage (Liu et al., 2017). In this case, probabilistic analysis can provide more rationale for decision making.

This paper begins with a review of operational modes of air ventilation systems, including detailed explanations of motor types. Reviews of economic analysis in terms of cost and benefit of ventilation and probabilistic analysis in the field of energy follow. Detailed descriptions of probabilistic social cost-benefit analysis models are presented. The model is validated through data obtained from real-world ventilation systems in which variable speed motors and inverters are installed by the authors. In the conclusion, the potentials of the model as a decision-making tool for the introduction of alternative systems into public facilities are discussed.

2. Air ventilation system in subway stations and economic analysis

2.1. Ventilation system in subway stations

The conventional ventilation systems installed in subway stations run fixed speed motors on predefined programmed schedules that can be turned off according to signals transmitted from control boards. This type of discrete operation is called “On/Off operation.” In this operational mode, actual status of indoor air pollutants is unknown to the system. As a result, it may consume unnecessary energy when the air quality meets the requirement (Lee et al., 2017). To cope with this problem, an operational method introducing available variable speed motors and inverters has been suggested (Kim et al., 2015; Lee et al., 2017). An inverter is the device controlling the revolving speed of motors by altering frequency.

Variable speed operation has been reported to reduce energy consumption by controlling the volume and speed of air flows by means of optimizing the motor revolving speed to meet the level of air quality. According to Kim et al. (2015), a 20% energy cost reduction is expected when this mode is introduced into subway station ventilation.

2.2. High-efficiency motors for air ventilation system

Electric motors are widely used to operate various industrial equipment i.e. pumps, fans, crushers, conveyor belts, mills, presses, etc. Their wide use promotes attempts to develop applications to improve efficiency. As consequences, high-efficiency motors have been developed and have contributed to reducing energy consumption. As minimum energy performance standards, the international motor efficiency classes (IE) were enacted and are defined in Standard IEC60034-30–1. Currently class IE2 (high-efficiency) and IE3 (premium-efficiency) induction Motors (IM) are mostly adopted for commercial use. The technical development of the IE4 motor type is completed and has been installed in various areas.

The synchronous reluctance motor (SynRM), one of the technologies for the IE4 motor type, has a saliency ratio structure that can produce a significant reluctance torque to maintain power density when using an inverter (Lin et al., 2016; Aarniovuori, 2016; Liu and Lee, 2018). It can control the speed and torque when installed with the inverter, resulting in energy saving from variable flow pumps and fan applications (de Almeida et al., 2014). Despite the advantages, the cases in which SynRM has been introduced in underground subway stations have not been reported.

2.3. Economic analysis of air ventilation systems

Özahi et al. (2017) analyzed the outcomes of a variable refrigerant fluid (VRF) system implemented in a social and cultural center building, by comparing to a conventional HVAC (Heating, Ventilation, and Air Conditioning) system. Cost items were divided into initial cost, operating cost, and maintenance cost, and the benefit considered is only electricity cost. In general, costs that occur during the use of ventilation systems consist of purchasing cost, installation costs, and energy costs and the sum of these is called Life-Cycle Cost (LCC). The LCC method is an effective tool for assessing the initial investment and future costs of projects during the total life cycle of the system (Ozyogurtcu et al., 2014). Ozyogurtcu et al. (2011) conducted an economic analysis on various heating, ventilation, and air conditioning modes for an operating a room in Turkey. The cost-related items were classified into initial cost, operating cost, and maintenance cost. In their later research, Ozyogurtcu et al. (2014) analyzed the economic benefits of ventilation systems introducing exhaust air heat recovery, electrical heaters, and solar energy. They classified cost-related items into system-related cost, installation cost, maintenance cost, and energy consumption cost. Kwong et al. (2017) undertook an energy conservation potential analysis and a cost–benefit analysis of a slab-integrated radiant cooling system in Malaysia. They stated that a cost–benefit analysis was required to provide the data necessary to recover the initial investment. This paper classifies cost-related items into initial costs and operational costs and includes the amount of energy saving in the analysis as a beneficial element.

Other studies with economic analyses on energy-saving systems in buildings are as follows. Perini and Rosasco (2013) performed an economic analysis on the introduction of green façades and living wall systems. Liu et al. (2014) analyzed green building energy efficiency technology applications in China. Fudholi et al. (2013) conducted an economic analysis on double-pass solar collectors with and without fins. Chen and Fulin (2016) performed an economic analysis on building intelligent systems. Delisle and Kummert (2016) analyzed integrating building-integrated photovoltaic-thermal air systems with thermal energy recovery into energy-efficient homes. Liu et al. (2014) conducted an economic analysis on green building energy efficiency technology applications in China. In all the previous studies, initial costs, and maintenance and operational costs were accounted for in the analysis.

In previous studies, variables related to the performance of ventilation systems that influence operational costs were calculated according to a fixed load. Such a method is suitable only when systems operate according to a predefined level of load. However, in variable speed operations controlled by the dynamic loads according to the indoor and outdoor environmental conditions, performance-related variables need to be regarded as a random variable. For instance, ventilation system loads are determined by the air quality measured by level of various air pollutants such as CO_2, particulate matter, radon, and fungi, which are affected by both indoor and outdoor air conditions. In this context, random variables can be clarified as internal and external air pollutants. However, since the presence of particulate matter represents a higher potential risk to human health than that of other air pollutants (Kim et al., 2015), the particulate matter is considered as an indicator of air pollution inside the underground subway station.