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Evaluation of a rapid LMP-based approach for calculating marginal unit emissions

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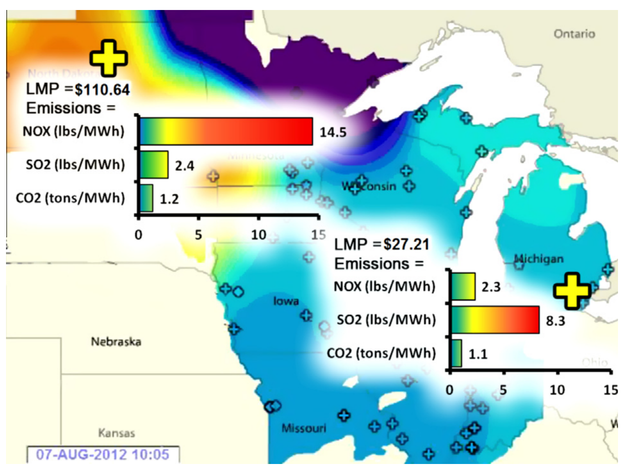
HIGHLIGHTS

- Pollutant emissions estimated based on locational marginal price and eGRID data.
- Stochastic model using IEEE RTS-96 system used to evaluate LMP approach.
- Incorporating membership function enhanced reliability of pollutant estimate.
- Error in pollutant estimate typically <20% for CO_2 and <40% for NO_X and SO_2.

GRAPHICAL ABSTRACT



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ABSTRACT

To evaluate the sustainability of systems that draw power from electrical grids there is a need to rapidly and accurately quantify pollutant emissions associated with power generation. Air emissions resulting from electricity generation vary widely among power plants based on the types of fuel consumed, the efficiency of the plant, and the type of pollution control systems in service. To address this need, methods for estimating real-time air emissions from power generation based on locational marginal prices (LMPs) have been developed. Based on LMPs the type of the marginal generating unit can be identified and pollutant emissions are estimated. While conceptually demonstrated, this LMP approach has not been rigorously tested. The purpose of this paper is to (1) improve the LMP method for predicting pollutant emissions and (2) evaluate the reliability of this technique through power system simulations. Previous LMP methods were expanded to include marginal emissions estimates using an LMP Emissions Estimation Method (LEEM). The accuracy of emission estimates was further improved by incorporating a probability distribution function that characterize generator fuel costs and a membership function (MF) capable of accounting for multiple marginal generation units. Emission estimates were compared to those predicted from power flow simulations. The improved LEEM was found to predict the marginal generation type approximately 70% of the time based on typical system conditions (e.g. loads and fuel

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costs) without the use of a MF. With the addition of a MF, the LEEM was found to provide emission estimates with errors typically less than 25% for CO_2, and less than 50% for SO_2 and NO_X. Overall, the LEEM presented provides a means of incorporating pollutant emissions into demand side decisions.

Nomenclature

C_i	cost of generation for generator i ($/MW h)
F_i	($/MMBtu) fuel price of generator i
CO_2	carbon dioxide
ef_i	emission factor for generator i
eGRID	US EPA's Emissions & Generation Resource Integrated Database
ER_i	emission rate of a specific pollutant from plant i
f_i	degree of membership for generator i
ISO	independent system operator
lb	pounds
k_{i2}, k_{i1} and k_{i0}	polynomial coefficients used to model the heat rate
LEEM	LMP emission estimation method
LME	locational marginal emission
LMP	locational marginal price
MATS	Mercury and Air Toxics Standards
MF	membership function
MISO	Midwest Independent System Operator
MMBtu	million metric British thermal units
MW h	megawatt hour
N_{bus}	total bus number
NG_i	net generation at plant i
NO_X	nitrogen oxides
p_i	power output (MW) of generator i
PDF	probability distribution function
RFCM	Reliability First Corporation Michigan
RTO	transmission organizations
SO_2	sulfur dioxide
μ	mean
σ	standard deviation
P_i	active power output of generator i
H_i	average heat rate of a plant (MMBtu/MW h)

1. Introduction

Electric power generation is a major source of air pollution. In 2010, power plants were responsible for 64% of SO_2 emissions, 16% of NO_X emissions, 40% of CO_2 emissions, and 68% of mercury air emissions in the US [1]. In the US power generation and energy demand are coordinated through regional energy markets managed by regional transmission organizations (RTOs) and independent system operators (ISOs). Because each ISO functions differently the amount of information that is made available to the public varies. Annual air pollutant loads from electrical generation are well documented for all regions due to reporting requirements by the US Environmental Protection Agency (EPA) and Energy Information Administration (EIA). However, real-time and spatially accurate information describing emissions is not easily obtained. This lack of transparency hinders the ability to make control decisions based on the amount of emissions that would be generated at any time. To quantify changes in emissions due to real-time demand controls, a model has been developed to estimate changes in pollutant emissions based on locational marginal prices (LMPs) [2]. While the original method provided a theoretical construct for estimating pollutant loads that could be used to drive demand-side decisions it (1) lacked regional specificity regarding pollutant emission factors, (2) was unable to account for more than one marginal unit, and (3) has yet to be validated. The purpose of this paper is to enhance the LMP Emission Estimation Method (LEEM) by addressing the first two short comings and verify its effectiveness.

LMPs are the wholesale electricity prices used by most RTOs and ISOs to efficiently manage the electric transmission system [3]. LMPs are locational, because they are published for thousands of node locations, and marginal because they represent the price for the next incremental unit of load at a particular time and place [4,5]. In other words, LMPs represent the cost to generate and deliver the next MWh of electricity [6] and take into account three things: the cost of generation, transmission constraints, and system losses [2]. If system losses are negligible, then LMP is a function of system constraints and the cost of generation. A constraint occurs when a physical limitation(s) of the transmission network is reached, making the transmission of electricity from the cheapest source to the demand inefficient or impossible. In these locations differences in LMPs will be observed across the line constraint and, as a result, different marginal units can be observed across the line constraint.

LEEM utilizes the LMP to identify the pollutant emission profile (i.e. emission factors) of a marginal generator, based on fuel type, for a given location and time [2]. The use of LMPs to estimate air emissions is powerful, because near real-time LMPs are publically available for many locations [7]. If real-time estimates for air emissions were made widely available, it may be possible to shift demand (spatially and temporally) to reduce air emissions due to power generation. This is particularly true for large water transmission systems where energy demand can be shifted slightly without negatively impacting system performance.

Central to the LEEM is the ability to identify the type of marginal generation unit based on the LMP. The marginal unit is the generator capable of supplying that next unit of energy at the cheapest rate. In other words, it is the most expensive generator that is currently dispatched, and therefore, will be the first unit to be incrementally adjusted due to changes in system demands [8]. Since the marginal generator will adjust to changes in demand, each incremental change in electrical use will result in an associated change in pollutant emissions.

Electricity markets in the US encourage utility participants to place generation bid prices based on generation costs. The cost of generation for each power plant can be reasonably approximated using publicly available data [9,10] and calculated as the price of fuel multiplied by the heat rate of that plant. Fuel prices are a function of the type of fuel used. Since the cost of generation is known for many power plants, LMP ranges associated with each fuel type can be determined for similar plants. Additionally, plants with the same primary fuel type are found to have similar air emission profiles. After an LMP is used to estimate the fuel type of the marginal unit, air emissions associated with that type of fuel can be estimated. Various public data sources can be used to estimate emis-