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The air quality and human health effects of integrating utility-scale batteries into the New York State electricity grid

Elisabeth A. Gilmore [a,b,*], Jay Apt [a,c], Rahul Walawalkar [a,d], Peter J. Adams [a,e], Lester B. Lave [a,c]

[a] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[b] Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[c] Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[d] Customized Energy Solutions, Philadelphia, PA 19102, USA
[e] Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

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ABSTRACT

In a restructured electricity market, utility-scale energy storage technologies such as advanced batteries can generate revenue by charging at low electricity prices and discharging at high prices. This strategy changes the magnitude and distribution of air quality emissions and the total carbon dioxide (CO_2) emissions. We evaluate the social costs associated with these changes using a case study of 500 MW sodium–sulfur battery installations with 80% round-trip efficiency. The batteries displace peaking generators in New York City and charge using off-peak generation in the New York Independent System Operator (NYISO) electricity grid during the summer. We identify and map charging and displaced plant types to generators in the NYISO. We then convert the emissions into ambient concentrations with a chemical transport model, the Particulate Matter Comprehensive Air Quality Model with extensions ($PMCAM_x$). Finally, we transform the concentrations into their equivalent human health effects and social benefits and costs. Reductions in premature mortality from fine particulate matter ($PM_{2.5}$) result in a benefit of 4.5 ¢ kWh^{-1} and 17 ¢ kWh^{-1} from displacing a natural gas and distillate fuel oil fueled peaking plant, respectively, in New York City. Ozone (O_3) concentrations increase due to decreases in nitrogen oxide (NO_x) emissions, although the magnitude of the social cost is less certain. Adding the costs from charging, displacing a distillate fuel oil plant yields a net social benefit, while displacing the natural gas plant has a net social cost. With the existing base-load capacity, the upstate population experiences an increase in adverse health effects. If wind generation is charging the battery, both the upstate charging location and New York City benefit. At $20 per tonne of CO_2, the costs from CO_2 are small compared to those from air quality. We conclude that storage could be added to existing electricity grids as part of an integrated strategy from a human health standpoint.

1. Introduction

Electric energy storage (EES) can decouple the time of electricity generation from its consumption, by storing electricity or energy to provide electricity when needed [1]. This can provide a range of benefits including reducing the need for new electricity generation capacity to meet peak electricity demand, relieving strain on transmission and distribution (T&D) infrastructure and supporting variable renewable sources such as wind [2,3]. Another benefit of EES installations is that they are easier to site than conventional power plants, allowing them to be located where electricity and generation capacity is most valuable. For example, Walawalkar et al. [4] examined the revenue opportunities for a sodium–sulfur (NaS) battery in the New York Independent System Operator (NYISO) electricity markets. Using optimistic assumptions about the capital cost, Walawalkar et al. found that the battery could operate profitably 65% of the time in New York City through energy arbitrage and by receiving payments for having available generation capacity in the installed capacity market [4]. Presently, the capital costs are almost double those assumed in Walawalkar et al. [4]; however, given the revenue opportunities in NYC, this would be an attractive site if the capital costs decrease, since energy arbitrage revenues are high there.

One reason these facilities may experience fewer barriers to siting is that at the point of use, the batteries have no emissions. This

* Corresponding author at: Department of Engineering and Public Policy, Carnegie Mellon University, 129 Baker Hall, 5000 Forbes Ave, Pittsburgh, PA 15213, USA. Tel.: +1 412 268 2670; fax: +1 412 268 3757.
E-mail addresses: eagilmor@andrew.cmu.edu (E.A. Gilmore), apt@cmu.edu (J. Apt), rahul@ces-ltd.com (R. Walawalkar), petera@andrew.cmu.edu (P.J. Adams), lave@cmu.edu (L.B. Lave).

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could be especially beneficial in highly populated urban load centers where the battery would displace dirtier generators, known as peaking plants, installed to meet peak electricity demand [5]. Depending on the location and type of generator used to charge the battery and the generator displaced by the battery, however, there may be net positive or negative social costs in terms of air quality, exposure and human health. In addition, there are also equity concerns about shifting emissions from one location to another. Many analyses investigating air quality effects look only at emissions. For example, Denholm and Holloway [6] investigated a system composed of a new non-adiabatic compressed air energy storage (CAES) charged with existing older coal-fired generators. Restricting their analysis to the change in total emissions, they found a benefit in terms of total carbon dioxide (CO_2) emissions due to switching from coal. By contrast, they found that the storage device does not bring the generator into compliance with the air quality emission limits from the New Source Performance Standards (NSPS) [6]. An emissions-only analysis for air quality issues, however, does not account for changes in the spatial and temporal distribution caused by charging and discharging the battery. Emissions must also be converted to their equivalent ambient concentrations before they can be used to characterize exposure or allow for the quantification of human health effects. Finally, an emissions analysis cannot account for the most pernicious pollutants with respect to human health, ozone (O_3) and a portion of the particulate matter with aerodynamic diameter less than 2.5 μm or fine particulate matter ($PM_{2.5}$), which is formed as a result of chemical reactions of the directly emitted chemical species [7].

The most comprehensive tool for converting emissions to ambient concentrations is a chemical transport model (CTM). CTMs have been employed to predict changes in air quality from distributed generation (DG) on the same scale as utility-size batteries. For example, Gilmore et al. evaluated the air quality effects of using diesel generators with and without emission controls for meeting peak electricity demand in New York City [8]. Similarly, Rodriguez et al. employed a CTM to evaluate the change in ambient air quality from introducing varying amounts of different forms of DG into California. Depending on the magnitude, location and type of DG, they found decreases and increases in ambient concentrations of O_3 and $PM_{2.5}$ [9]. Carreras-Sospedra et al. ran similar scenarios in the Northeast United States, but retired older base-load generation such as pulverized coal plants [10]. By contrast to Rodriguez et al. [9], O_3 and $PM_{2.5}$ decreased in these scenarios. To the best of our knowledge, there has been no study which has used CTMs to evaluate the air quality effect of integrating EES into electricity grids.

In this paper, we isolate the changes in air quality and human health effects by modeling a single NaS battery (or a number of NaS installations) located in New York City, charging with off-peak base-load resources in the NYISO region. First, we identify the types of plants and the frequency that each type of plant would be used for charging by constructing a dispatch curve for the NYISO. Second, we evaluate the changes in air quality, human health effects and the net costs or benefits of changes in air quality and human health effects for combining the battery with individual charging plants that exist in the NYISO as well as new generation such as wind capacity. We conduct the air quality modeling with a 'state of science' chemical transport model, the Particulate Matter Comprehensive Air Quality Model with extensions ($PMCAM_x$) [11]. Third, we evaluate the change in carbon dioxide (CO_2) and compare these costs and benefits to those from air quality. Finally, we investigate the distribution of the costs and benefits in the NYISO area. We consider the social cost from changes in emissions only and do not include other potential social costs and benefits such as reducing peak electricity prices.

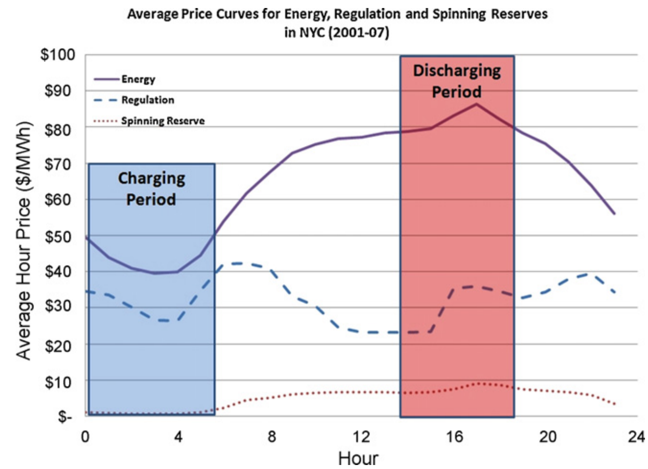

Fig. 1. Charging and discharging periods and average price received as a function of hours of day. The price curves for energy, regulation and spinning reserve for New York City (NYC) as a average from 2001 to 2007 are also shown separately.

2. Methods and data

For our case study, we site a 500 MW NaS battery facility (or 500 MW of cumulative battery installations) in New York City, New York. We assume that the battery discharges from 1 to 5 p.m. and charges from 1 to 6 a.m. (Eastern Standard Time) during summer. The additional hour of charging time is required to account for the battery round-trip charging efficiency of 80%. This scenario results in 2000 MWh (500 MW × 4 h) of electricity provided per day by the battery. Using real-time prices from the NYISO, Walawalkar et al. [4] showed that this operating scenario maximized revenue for these facilities. We show the discharge and charging periods as well as the average spot market prices in Fig. 1. This configuration is also important from an air quality perspective since New York City is highly populated, and there is a wide range of generators that could be used for charging in the NYISO region.

2.1. Charging and displaced plants

First, we develop a list of the potential power plant types used for charging and plants displaced by the battery. While the NYISO has information on the actual charging and displaced plants, it does not release this data publicly. To develop independent estimates of the type of plants used and the frequency that each plant is dispatched, we develop a curve which approximates the dispatch order of the plants in the NYISO as a function of their marginal cost (MC) calculated using Eq. (1).

$$MC = HeatRate \cdot FC + VOM \quad (1)$$

where MC is the marginal cost of generating electricity (in $\$\,kWh^{-1}$), HeatRate is the efficiency of the generator (in $Btu\,kWh^{-1}$), FC is the cost of fuel (in $\$\,Btu^{-1}$), and VOM is the operating and maintenance that occurs from generating (in $\$\,kWh^{-1}$).

The generators are sorted from lowest to highest MC, plotting the MC versus the cumulative generation capacity available at that MC or lower [12]. We then intersect this curve with the amount of electricity demanded in each hour to determine which plants would be available for charging as well as to approximate the frequency that a plant or fuel type is used. We take the loads from the NYISO [13]. More information on calculating the frequency can be found in Walawalkar [14].

For the data on heat rates and available generation capacity, we evaluate and compare the United States Environmental Protection Agency (USEPA)'s Emissions & Generation Resource Integrated

Database 2006 (eGRID2006) [15] and the Ventyx Velocity Suite, a private dataset [16]. The two datasets are based on similar data from the Energy Information Administration (EIA) [17]. Each dataset contains a different amount of detail about the facilities and generators in the system as well as makes different assumptions about generators that can operate on two different fuels (e.g. dual fuel generators that can operate on natural gas or fuel oil) and the amount of available generation. Differences in generator names and other features between the datasets make a direct comparison infeasible. We choose eGRID2006 since it is publicly available, but compare our results to the curve produced by using the Ventyx dataset to evaluate our results.

We multiply the heat rates in eGRID2006 by fuel prices consistent with the costs for electricity generation in New York State, obtained from the EIA [17,18]. For each plant type that we identify, we map the plant type to indicative facilities in the NYISO. Coordinates for these facilities are obtained from the Facility Registry Service (FRS) managed by the USEPA [19].

2.2. Emission factors and air quality modeling

To model the air quality effects, we develop emission factors (EFs) for each fuel-generator type. Emission factors measure the amount of a pollutant released (in g) per unit of electricity generated (in kilowatt-hours, kWh). These EFs can vary significantly for any given fuel type, depending on plant configuration, operating conditions, and emission control technologies. The EFs in this work are derived from the USEPA AP-42 compilation [20], the observed values for NYISO generators in eGRID2006 [15] and the Integrated Environmental Control Model (IECM) for coal [21]. For the coal plants, we model three different configurations with the IECM: a coal plant without emission controls, a plant with modern emission controls, and an IGCC. We specify a bituminous coal consistent with the quality of coal delivered for electricity generation in New York State with 8.1% ash and 2.2% sulfur [22]. For the plant with emission controls, we add an electrostatic precipitator (ESP) to reduce $PM_{2.5}$, flue gas desulfurization (FGD) to reduce sulfur dioxide (SO_2) and selective catalytic reduction (SCR) to reduce nitrogen oxides (NO_x). Emission factors for CO_2 emissions and heat rates are derived from observed values for NYISO generators in eGRID2006 and supplemented by Graus et al. [23]. With the possibility of regulations restricting CO_2 emissions, some new coal plants may be constructed with carbon capture and storage CO_2 emission controls. We do not model CO_2 emission controls on any plants. We show the emission factors used in this work in Table 1.

The EFs from Table 1 are split into species consistent with the representation of the chemical species in $PMCAM_x$. The NO_x emissions are split into 85% nitrogen oxide (NO) and 15% nitrogen dioxide (NO_2). The $PM_{2.5}$ mass is split equally into elemental (EC) and organic (OC) carbon. The $PM_{2.5}$ mass is also separated over six size bins representing aerodynamic diameter less than 2.5 μm. The total emissions are calculated by multiplying the speciated EF by the amount of electricity generated (i.e., 2000 MWh per day for the displaced plant and 2500 MWh per day for the charging plant). We allocate these emissions to the appropriate hours and plant locations. Since the emissions are based on literature and average values rather than emissions specific to that plant, the results should not be interpreted as the effect of altering emissions at the actual plant. Rather, these results are broadly indicative of the emissions from each plant type. We consider only emissions associated with electricity generation.

To transform the total emissions to ambient concentrations, we employ the Particulate Matter Comprehensive Air Quality Model with extensions ($PMCAM_x$). $PMCAM_x$ is a 'state of science' CTM that simulates the emission, advection (convection), dispersion, gas and aqueous phase chemical reactions, and dry and wet deposition for 35 gaseous species, 12 radical species and 13 aerosol species in 10 size bins on a 3D Eulerian grid. Additional modules simulate the dynamic behavior (coagulation, condensation, and nucleation) of aerosols species. Details and evaluation of the model can be found in Gaydos et al. [11] and Karydis et al. [24]. We model the ambient air quality concentrations for each charge–displace combination for a period of 2 weeks in July 2001 (July 15–28), corresponding to a period when $PMCAM_x$ has been extensively evaluated. We present our results as the average ambient concentration over this 2-week period. We interpolate the available meteorological fields produced by the mesoscale model, known as MM5 [25], and the baseline emission files from the Lake Michigan Air Directors Consortium (LADCO) [26] from a 36 km horizontal grid resolution to a 12 km grid to better resolve the change in emissions and the resulting concentrations. The vertical grid is discretized into 14 layers from the surface to 6 km. The lowest model layer is slightly less than 30 m thick vertically. For the coal plant, the emissions are modeled as emitted into the second layer from the ground. Emissions from all other plants are modeled as emitted into the first layer. This is consistent with the stack heights of these facilities.

2.3. Human health effects and social costs

We evaluate the human health effects and the equivalent social cost for each separate charging plant and displaced plant, for each potential charge–displace combination, and for the entire system (i.e., accounting for the frequency that each plant is used for charging). For any given health endpoint, we calculate the change in that endpoint using concentration-response (CR) functions and multiplying by the exposed population, shown in Eq. (2). The total social value is then generated by multiplying each health endpoint by the dollar value associated with this endpoint, known as a "willingness to pay (WTP)", shown in Eq. (3). We express the resulting social cost or benefit as a value normalized by the electricity provided by the battery (e.g. 2000 MWh per day).

$$\Delta \text{health endpoint}_i = [1 - \exp(-\beta_i \cdot \Delta \text{conc})] y_{o,i} \cdot \text{pop} \quad (2)$$

$$\text{SC} = \sum_{i=1}^{n} \Delta \text{health endpoint}_i \cdot \text{WTP}_i \quad (3)$$

where i is each different health endpoint, n is the total number of different health endpoints, β is the strength of the relationship between the change in ambient concentration of a given pollutant and the endpoint (in cases per 24-h average ppb or cases per 24-h average $\mu g\,m^{-3}$), Δconc is the change in ambient concentration of a given pollutant (in 24-h average ppb or 24-h average $\mu g\,m^{-3}$), pop is the population exposed to the change in concentration, SC is the social cost (in $), WTP is the "willingness to pay" to avoid the adverse health effect (in $), and y_o is the baseline incidence of the adverse health effect in the absence of the pollutant.

We use WTPs, y_o, and population distribution from the Environmental Benefits Mapping and Analysis Program (BenMap), version 2.4.85 [27]. We also extend the BenMap population and incidence values to include Canada with population from the Gridded Population of the World dataset [28]. We focus on the change in premature mortality from O_3 and $PM_{2.5}$. To evaluate mortality due to changes in O_3, we use a 24-h averaging metric from Bell et al. [29–31]. To evaluate the long-term (annual) effects of $PM_{2.5}$ and mortality, we use a fixed pooling of CR relationships from Pope et al. [32] and Laden et al. [33]. We assume that the average of our 14 modeled days is representative of the change in ambient concentrations that would be observed on any given summer time day. We restrict our analysis to the summer as previous analysis found that the battery will derive most of its revenue in the NYISO summer capability period from May 1st to October 31st [4]. To convert premature mor-

Table 1
Emission factors in g kWh^{-1} and the heat rate in Btu kWh^{-1} for plant types [15,20,21,23].

Plant type	Nitrogen oxides, NO_x (g kWh^{-1})	Sulfur dioxide, SO_2 (g kWh^{-1})	Fine particulate matter, $PM_{2.5}$ (g kWh^{-1})	Carbon dioxide, CO_2 (g kWh^{-1})	Heat rate (Btu kWh^{-1})
Uncontrolled pulverized coal	2.20	2.66	0.582	950	10,200
Controlled pulverized coal	0.70	1.10	0.058	970	10,400
IGCC coal	0.45	0.23	0.038	920	9,900
Residual fuel oil boiler	1.00	2.35	0.139	920	11,700
Natural gas boiler	0.67	~0	0.037	610	11,700
Distillate fuel oil turbine	1.53	0.093	0.158	910	12,500
Natural gas turbine (simple cycle)	1.31	~0	0.036	650	12,500
Natural gas turbine (combined cycle – NGCC)	0.186	~0	0.023	360	6,900

tality into dollars, we model the WTP for a premature death as the value of a statistical life (VSL) with a Weibull distribution with a mean of $7.5 million (in 2005 dollars) (Weibull scale parameter: $8,300,000; Weibull shape parameter: 1.5096). We show 5% and 95% confidence intervals to capture the uncertainty in the health endpoints and WTP estimates. A range of morbidity effects such as respiratory and cardiovascular events and reduced activity days are also associated with changes in air quality, but previous studies have found that these contribute less than 15% to the overall social cost [34,35].

In addition to calculating the cost of the change in human health effects for the separate charging and displaced plants and for the charge–displace combinations, we are also interested in evaluating the overall social cost of operation for the NYISO. As shown in Eq. (4), the overall cost to the system is the social value of each possible charge plant and each possible displaced plant multiplied by the frequency with which that plant type is used for charging or displaced over the summer time period.

$$\text{Overall economic efficiency} = \sum_{1}^{j} \text{SC}_j \cdot \text{XMP}_j + \sum_{1}^{k} \text{SC}_k \cdot \text{XMP}_k \quad (4)$$

where j is the number of possible charging plants, k is the number of possible displaced plants, SC is the social cost for each plant used for charging or is displaced (in $), and XMP is the fraction that each plant type is used for charging or displaced.

We use the frequencies (XMP) that we develop using our estimated dispatch curve and intersecting the supply curve with actual NYISO hourly loads.

3. Results and discussion

3.1. Dispatch curve

In Fig. 2, we show two dispatch curves as estimated using eGRID2006 as well as the curve provided by Ventyx. We also show the approximate low, average, and high demand in the NYISO area during the charging period. We produce two curves from the eGRID2006 dataset since several turbines and boiler-steam turbine plants can operate on either natural gas or fuel oil. This is the result of the Minimum Oil Burn rule [36]. This rule requires that these plants operate on a minimum level of a fuel other than natural gas during periods of high demand. Since we do not know which fuel is being used during any given hour, we assign the entire plant to natural gas or fuel oil and compare the dispatch frequencies from these two curves as a bounding analysis. This curve also assumes that there are no net imports of electricity from outside the NYISO.

We note two limitations of using eGRID2006 for our dispatch curve. First, while eGRID2006 presents the total capacity at a given facility, the available capacity for any given generator is a function of the hour of the day and the day of the year due to forced outages, maintenance schedules and reserve margins. Since we do not have this information, we capture the availability of the generators by multiplying the total capacity for each generator by the NYISO system availability. We find that generation in the NYISO system has an availability of approximately 87%. Second, the eGRID2006 dataset contains the heat rate by facility only. Any given facility, however, may include several units which have different heat rates and may operate on different fuel types. Aggregating this heat rate and fuel types over several units could misallocate generation to either a lower or higher MC.

Comparing our dispatch curves to the curve provided by Ventyx, we observe minor differences. This is due primarily to different assumptions about the cost of fuel. For example, between 25,000 and 32,000 MW, Ventyx assumes higher fuel prices for distillate fuel oil and residual fuel oil. Also, Ventyx calculates the cost of dispatching a generator as a weighted average of the cost for a given fuel and the fraction of the electricity produced by the fuel over the time period of interest. We judge this approach unsatisfactory as it does not indicate which fuel is actually being used.

3.2. Charging and displaced plants

We find that the type of plant employed for charging could be fueled by coal, natural gas or residual fuel oil. We identify four candidate plants: a pulverized coal plant, natural gas fueled combined cycle turbine, a residual fuel oil fueled boiler-steam turbine, and a natural gas fueled boiler-steam turbine. We map these fuel types to actual plants in the NYISO. In Fig. 3, we show the approximate locations of these plants.

To bound the effect of a coal plant, we model a plant without any emission controls as well as a plant with modern emission controls. In New York, coal plants have modern emission controls as a result

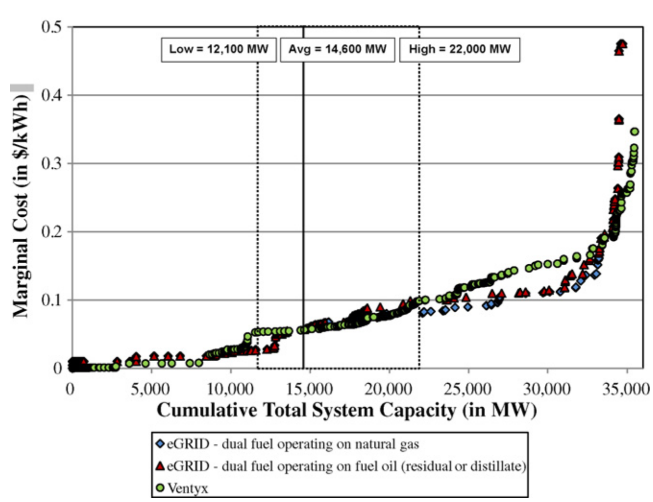

Fig. 2. Dispatch curves for NYISO for eGRID and Ventyx. This curve shows the order that the electricity generators in the NYISO are dispatched as a function of cost in \$ kWh^{-1}. The dispatch curve for eGRID is shown with all dual fuel enabled generators operating on natural gas and all dual fuel generators operating on fuel oil.

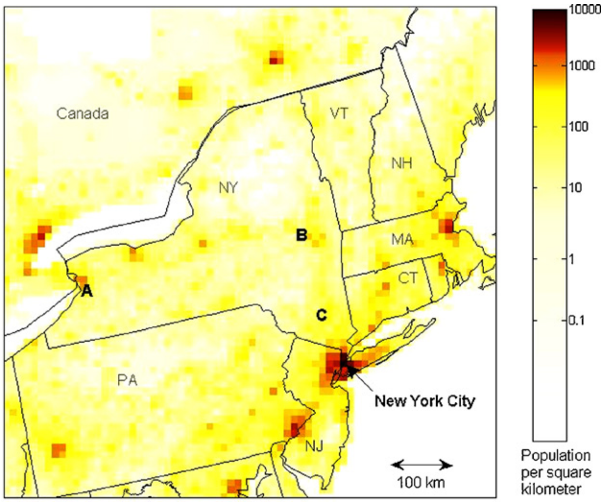

Fig. 3. Location of charging and displaced generators. The coal plants are modeled in Western New York State at A. The natural gas fueled combined cycle turbine is modeled at B. The residual fuel oil or natural gas boiler-steam turbine is located at C. The battery displacing the natural gas or distillate fuel oil peaking turbine is located in New York City as indicated by the arrow. A charging plant, either a natural gas or residual fuel oil boiler-steam turbine, may also be located in New York City. Population per 1 km by 1 km grid cell is shown. CT, Connecticut; MA, Massachusetts; NH, New Hampshire; NJ, New Jersey; NY, New York; PA, Pennsylvania; VT, Vermont.

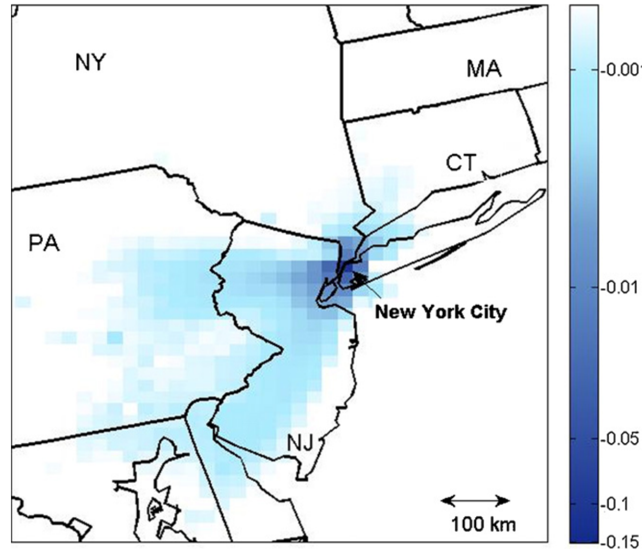

Fig. 4. Change in daily mean $PM_{2.5}$ (in $\mu g\,m^{-3}$) concentrations as an average of 2 weeks of simulation for displacing a distillate fuel oil peaking turbine in New York City. The wind patterns account for the cloud of ambient concentrations. The white box shows the location of New York City.

of legal settlements to a New York State lawsuit against dirtier coal plants in 2005 [37]. For the natural gas and residual fuel oil fueled charging plants, we also model the possibility that the charging plant is co-located with the battery in New York City. Nuclear and hydro-electric facilities are not marginal plants in the NYISO system at night during the summer. These plants are classified as must-run plants, and the minimum load during the summer months in New York State exceeds their combined capacity.

In addition to the existing plant types, we evaluate two long-run possibilities for the charging plant. First, we model a coal plant as an integrated gas combined cycle (IGCC) facility. This facility would reduce emissions in a manner consistent with an emission-based air quality rule such as the USEPA Clean Air Interstate Rule (CAIR) [38]. Under this type of regulation, the total emissions of a given pollutant (e.g. NO_x or SO_2) are capped, and each generator must procure sufficient credits to cover its emissions [39]. Facing a shortfall, a generator can purchase additional credits from another generator which has reduced its emissions, or it can reduce its own emissions by emission controls or other modifications to the facility. Under some circumstances, it may become uneconomical for the generator to continue to operate. We limit our modeling to a generator which chooses to reduce its emissions. Second, we model base-load wind as the marginal plant. The New York Renewable Portfolio Standard (RPS) mandates that renewable sources provide 25% of electricity in 2013 [40]. It is expected that 4.7% will be met by new generation and that substantial amounts of wind generation will be installed [41].

We assume that the battery would displace a simple cycle turbine (peaking plant) located in New York City. Due to the Minimum Oil Burn reliability rule, these plants may be operating on natural gas or another fuel, generally distillate fuel oil. Since we are unable to determine whether the peaking plant is operating on natural gas or distillate fuel oil, we investigate both a natural gas and distillate fuel oil simple cycle turbine. We note that in some cases, upstate generators provide peak electricity. We do not evaluate the potential that upstate generators would also be displaced by the battery, and as such, we do not model potential benefits from avoided thermal transmission loss (although any thermal benefits would likely be offset by battery inefficiency).

In Table 2, we show our estimates of the dispatch frequencies from intersecting our curve with actual system loads for the NYISO area. First, we present the frequencies if all plants that can operate dual fuel are using natural gas. Second, we present the frequencies if all plants that can operate on dual fuel are using fuel oil. We compare the social value to the system under these two cases.

3.3. Ambient air quality concentrations

In Fig. 4, we show the average change in concentration for $PM_{2.5}$ in $\mu g\,m^{-3}$ over the 2-week simulation for displacing a distillate fuel oil peaking turbine in New York City. Small decreases in $PM_{2.5}$ are observed due to a reduction in primary emissions with very small changes in the portion of $PM_{2.5}$ (secondary) that is formed by reactions of gases. In Fig. 5, we show the average change in concentrations of O_3 in ppb over the two simulation weeks. Small increases in O_3 are observed. These O_3 increases are consistent with the volatile organic compounds (VOC) to NO_x ratios predicted by $PMCAM_x$. When the initial ratio of NO_x to VOC is high (i.e., VOC-limited), adding more NO_x will decrease the formation of O_3. At lower ratios (i.e., NO_x-limited), the additional NO_x increases the formation of O_3. Urban centers tend to have high NO_x to VOC ratios, and hence, adding more NO_x leads to the observed increases [42]. Compared to displacing a distillate fuel oil fueled turbine, a nat-

Table 2
Estimated frequency NYISO plant types are used for charging the battery. To obtain the frequency estimates, the dispatch curve for either all dual fuel plants operating on natural gas or on fuel oil is intersected with observed hourly loads in the NYISO. Summing the number of hours that the load intersects a given fuel type and dividing by the number of hours yields the following frequencies.

Fuel type	Dual fuel plants operating as natural gas	Dual fuel plants operating as fuel oil
Coal plant	1.3%	1.3%
Natural gas plant	97.4%	42.6%
Fuel oil (residual or distillate)		52.6%
Other fuel types	1.3%	3.5%

Table 3
Average daily change from baseline concentration for $PM_{2.5}$ (in $\mu g\,m^{-3}$) and O_3 (in ppb) in New York City, the equivalent premature mortality (in cases per year) and social cost (in ¢ kWh^{-1}) from displacing 500 MW of distillate fuel oil and natural gas peaking generation for 4 h a day. 5% and 95% confidence intervals are shown for the health effects and social cost.

	DFO displaced	NG displaced
Daily mean change in $PM_{2.5}$ in New York City ($\mu g\,m^{-3}$)	−0.12	−0.03
Change in mortality (cases per year)	−9 (−3, −18)	−3 (∼0, −6)
Social cost from $PM_{2.5}$ (¢ kWh^{-1})	−16.6 (−4.15, −35.4)	−4.49 (−1.13, −9.60)
Daily mean change in O_3 (ppb)	+1.0	+0.85
Change in mortality (cases per year)	+7 (3, 10)	+6 (3, 9)
Social cost from O_3 (¢ kWh^{-1})	+13.7 (3.17, 25.6)	+11.7 (2.70, 21.9)

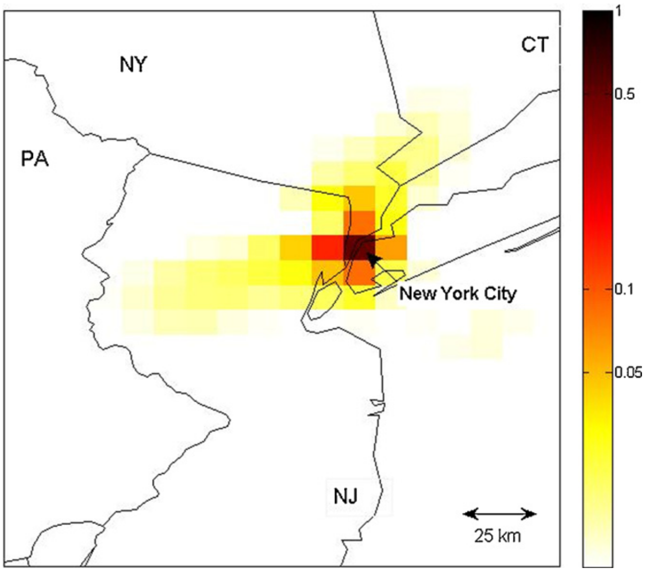

Fig. 5. Change in daily mean O_3 (in ppb) concentrations as an average of 2 weeks of simulation for displacing a distillate fuel oil peaking turbine in New York City. The wind patterns account for the cloud of ambient concentrations.

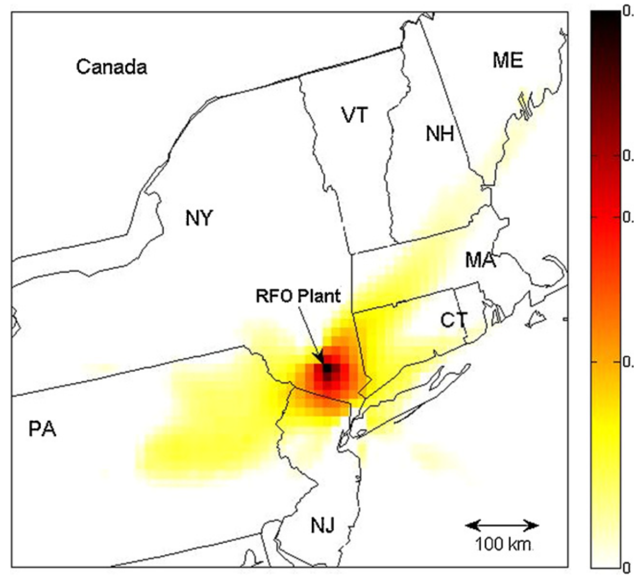

Fig. 7. Change in daily mean $PM_{2.5}$ (in $\mu g\,m^{-3}$) concentrations as an average of 2 weeks of simulation for charging with a residual fuel oil boiler-steam turbine plant. The wind patterns account for the cloud of ambient concentrations.

ural gas turbine yields the same spatial patterns for both O_3 and $PM_{2.5}$ with the magnitude of the change reduced by approximately the difference in the emissions between the two turbines. Differences in wind patterns over the 2-week modeling period account for the cloud of ambient concentrations for both $PM_{2.5}$ and O_3. As expected, the changes in ambient air quality are small for 500 MW of batteries. However, if 10–20% of peak load in New York City were handled by batteries, the observed changes in air quality would be much larger.

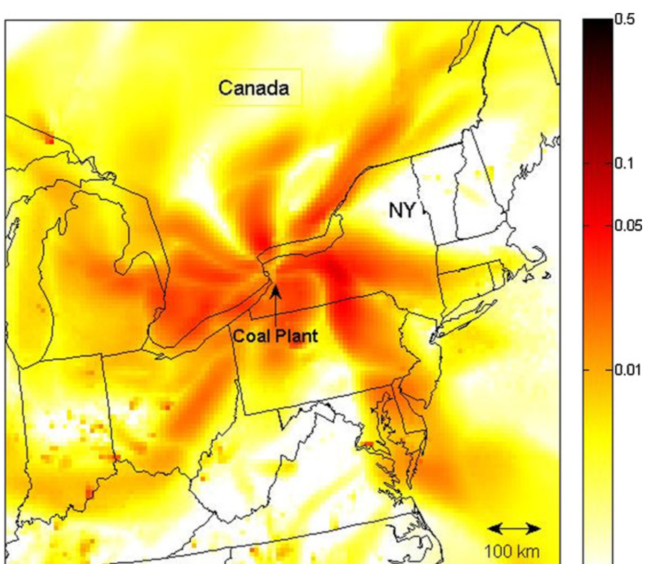

Fig. 6. Change in daily mean $PM_{2.5}$ (in $\mu g\,m^{-3}$) concentrations as an average of 2 weeks of simulation for charging with an uncontrolled coal plant. The wind patterns account for the cloud of ambient concentrations.

We show the average change in the concentration of $PM_{2.5}$ in $\mu g\,m^{-3}$ for an uncontrolled coal plant and for residual fuel oil boiler-steam turbine plant in Figs. 6 and 7, respectively. For $PM_{2.5}$, we observe small increases. For O_3, we show the average change in concentrations in ppb over the two simulation week for an uncontrolled coal plant (Fig. S1) and for a residual fuel oil boiler-steam turbine plant (Fig. S2) in the Supplementary Material. We observe increases and decreases in O_3 concentrations consistent with the modeled VOC/NO_x ratios. For a coal plant with emission controls and an IGCC, we observe the same spatial patterns for both O_3 and $PM_{2.5}$ as the uncontrolled coal plant. Similarly, we observe the same spatial patterns for a natural gas boiler-steam turbine plant as the residual fuel oil boiler. The change in ambient concentrations for the natural gas combined cycle plant is not shown since only very small changes are observed.

3.4. Changes in carbon dioxide emissions

In addition to the changes in air quality, there are changes in the total emissions of CO_2. In Fig. 8, we show the changes in total CO_2 emissions for each charge–displace combination and for the system using the frequency that each charging plant is dispatched. Similar to the changes in air quality, we find that displacing a distillate fuel oil peaking plant yields a benefit in more cases than a natural gas

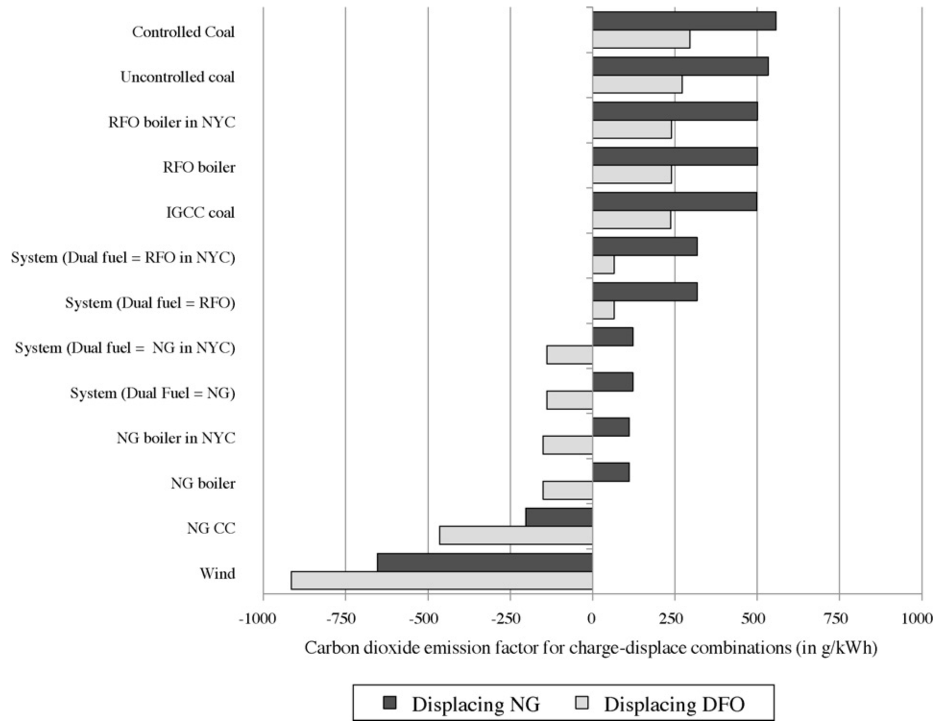

Fig. 8. The change in CO_2 emission factors (in g kWh^{-1}) for displacing a distillate fuel oil (DFO) and a natural gas (NG) peaking plant. The light grey bars are for different system-level charging plant combinations. Dual fuel indicates the type of fuel that is being used by a dual fuel charging plant (e.g. natural gas, NG, or residual fuel oil, RFO). NYC indicates that the charging plant is located in New York City.

peaking plant. If a natural gas peaking plant is displaced, only the more efficient natural gas combined cycle turbine or wind results in a net reduction in CO_2 per kWh of electricity generated.

3.5. Human health effects and social costs

In Table 3, we present the change from baseline concentrations for $PM_{2.5}$ and O_3 in New York City, the equivalent human health effects and social cost from displacing a natural gas and distillate fuel oil peaking plant, respectively. The values calculated in this work are slightly higher than other concentration – response type studies [43], but are within the range of values from the European ExternE project [7,44]. The higher values in ExternE result from denser populations in parts of Europe; these population densities are consistent with the population in the New York City region. Our values are also slightly higher as we normalize the social values over the amount of electricity discharged by the battery rather than the amount of electricity used for charging (e.g. 2000 MWh rather than 2500 MWh). Social costs for all charge–displace combinations with the 5% and 95% confidence intervals for $PM_{2.5}$ and O_3 are tabulated in Table S1 in the Supplementary Material.

In Figs. 9 and 10, we show the social costs from mortality from $PM_{2.5}$ and from CO_2 for each charge–displace plant combination for displacing a distillate fuel oil and natural gas peaking turbine, respectively. For the New York City region, we observe a social benefit from reducing $PM_{2.5}$. Adding the costs from increases in $PM_{2.5}$ associated with the charging plant, we still observe social benefits for displacing a distillate fuel oil unless an uncontrolled coal plant or a residual fuel oil boiler located in New York City is used for charging. For displacing a natural gas peaking plant, we find a social benefit only if cleaner generators are used for charging such as natural gas fueled generators and controlled coal plants.

To compare the social cost of the CO_2 emissions to those from air quality, we multiply the values in Fig. 10 by \$20 per tonne for CO_2. This price for CO_2 is consistent with the prices observed on the European Climate Exchange (ECX) [45]. The social costs from CO_2 range from −2.7 to 1.6 ¢ kWh^{-1}. In most cases, these costs are small compared to the costs from air quality. For a controlled coal plant, however, the costs from CO_2 can exceed the air quality benefits if a natural gas peaking plant is displaced.

We also evaluate the changes in mortality from O_3. The increases in O_3 from displacing a peaking plant in New York City leads to a social cost from increased mortality. These social costs decrease the benefit from reducing $PM_{2.5}$. For displacing a natural gas peaking

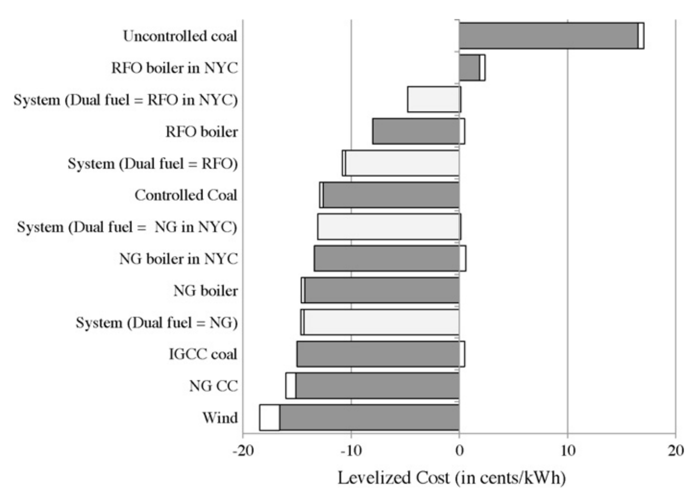

Fig. 9. Net social cost for $PM_{2.5}$ and CO_2 for displacing a distillate fuel oil peaking plant in ¢ kWh^{-1}. The dark grey bars are the $PM_{2.5}$ costs for each separate charge–displace combination. The light grey bars are the $PM_{2.5}$ costs for different system-level charging plant combinations. The white bars are the social costs for CO_2. Dual fuel indicates the type of fuel that is being used by a dual fuel charging plant (e.g. natural gas, NG, or residual fuel oil, RFO). NYC indicates that the charging plant is located in New York City.

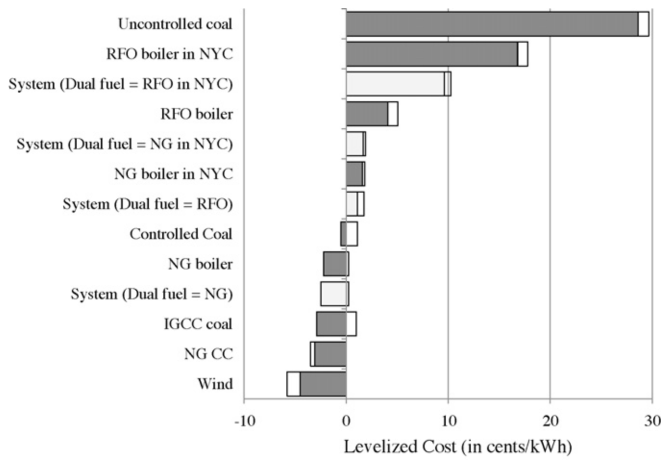

Fig. 10. Net social cost for $PM_{2.5}$ and CO_2 for displacing a natural gas peaking plant in ¢ kWh^{-1}. The dark grey bars are the $PM_{2.5}$ costs for each separate charge–displace combination. The light grey bars are the $PM_{2.5}$ costs for different system-level charging plant combinations. The white bars are the social costs for CO_2. Dual fuel indicates the type of fuel that is being used by a dual fuel charging plant (e.g. natural gas, NG, or residual fuel oil, RFO). NYC indicates that the charging plant is located in New York City.

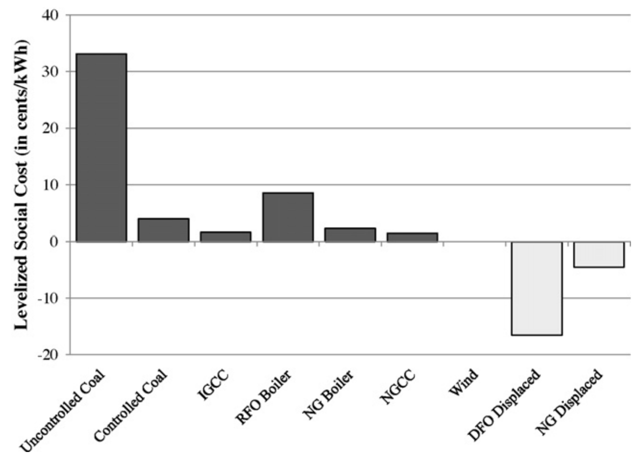

Fig. 11. The social costs for $PM_{2.5}$ for the charging generator and displaced peaking plant in ¢ kWh^{-1}. The dark grey bars are the social costs from charging the battery. The light grey bars are the social benefit from displacing the peaking plant in New York City.

plant, summing the social value from changes in mortality for $PM_{2.5}$ and O_3 results in a social cost for all possible charging plants. While the relationship between exposure to $PM_{2.5}$ and premature mortality is relatively well understood, the magnitude of the relationship between mortality and O_3 is subject to greater uncertainty [35]. As a result, we caution against a simplistic summing of O_3 and $PM_{2.5}$ social costs.

In addition to the social costs and benefits for each charge–displace combination, we also calculate the total system social cost for the battery. Using the frequency estimates in Table 2, we find an overall social benefit when a distillate fuel oil peaking plant is displaced for mortality from $PM_{2.5}$ only as well as the sum of mortality from $PM_{2.5}$ and O_3. If a cleaner natural gas peaking plant is displaced, there is a cost at the system-level in almost all cases unless all dual fuel plants are operating on natural gas. In this analysis, we use average values for heat rate and full-load emissions factors. Some generators, however, would be operating at partial load during off-peak periods [6]. Since most generators operate more efficiently at full-load conditions (e.g. lower average heat rate), the additional demand for charging the battery could potentially decrease the air quality emissions per kWh generated from these plants. Thus, this analysis may lead to an overestimation of the cost of integrating a battery in the NYISO. Again, better information about the dispatch order of the plants would be necessary to identify a plant operating at partial load.

We also separate the social cost of $PM_{2.5}$ into the charging and displaced portions to evaluate the distribution of the benefits and costs. We show the results in Fig. 11. In all cases except wind, a population located in the upstate portion of New York State experiences deterioration of ambient air quality and adverse human health effects. For charging plants located upstate, New York City may also experience a change in ambient concentrations. We find that this effect is small unless the charging plant is co-located with the battery; as a result, we do not separate the charging and discharging components for a co-located charging plant. In the case of the charging plant being co-located in NYC, the cost is imposed on the same population that observes the benefit from displacing peaking generation, reducing equity concerns.

If we consider only short-term effects (e.g. using existing NYISO generators), there are important distributional effects. In the long-term, the battery will also interact with new generation capacity and regulations affecting the electricity sector. Under a rule similar to CAIR, operating any of the charging plants may require the purchase of additional emission credits. If emissions allowances are purchased (assuming that no party is using banked allowances), then a reduction in emissions must be observed in another location. Since the premise of emission trading is that each generator in the trading group has emissions with approximately equal social cost [39], these trades should result in a net zero change in social cost. These benefits, however, may or may not accrue to the New York State populace depending on the location of the generator that sells the credits. It is outside the scope of this paper to evaluate potential trades. We do, however, investigate shifting the coal plant to an IGCC as a response to CAIR. We find that the IGCC has a significant benefit, reducing the social costs from charging to values in the same range as natural gas fueled options. The battery installation can also interact and support intermittent renewable resources. At the end of 2008, there was approximately 1.15 GW of installed wind capacity in New York State with a doubling expected in the next several years as a result of the RPS [16,46]. If wind is the charging plant, there could be no effect on the population at the charging location. In addition to cleaner charging plants, the IGCC and the wind turbines have the additional benefit of reducing the social cost for all electricity that is generated from that plant.

4. Conclusions

Depending on the charging plant and the displaced plant, there is a potential for a social cost or benefit from integrating battery storage into the NYISO. If dirtier New York City peaking plants are displaced by the battery and cleaner upstate facilities such as natural gas combined cycle plants are used for charging, a social benefit results. However, if natural gas peaking plants are displaced in New York City, there may be a social cost from charging with existing base-load generation with higher emissions in the NYISO such as a residual fuel oil boiler. Increases in O_3 in New York City from displacing NO_x emissions from either a distillate fuel oil or natural gas peaking plant also raise potential health concerns. We note, however, that the USEPA has promulgated progressively more stringent air quality standards affecting electricity generation. As a result, we expect that there will be more scenarios where the benefit from displacing peaking plants in the highly populated New York City will exceed the increase in air quality costs from the charging plant. Adding the costs from the change in CO_2 emissions does not alter these results, with the exception of using a controlled coal plant for charging and displacing a natural gas turbine.

Regardless of the overall value for a charge–displace combination, additional emissions may create an equity concern for the upstate population. Emissions trading under a rule such as CAIR might alleviate some of these issues. In the long-term, the battery could support cleaner generation, specifically base-load wind, improving both the overall efficiency and equity of the system.

At a system-level, the cost is a function of the type and location of the generators as well as the frequency that each plant is used for charging or is displaced by the battery units. Given the complexities of determining the dispatch order, we are unable to make more than an estimate of the system wide effect using public data. We recommend that the Federal Energy Regulatory Commission (FERC) task NYISO and other system operators to provide this data to allow for a comprehensive analysis of the changes in air quality and human health before siting new battery facilities. This would allow the batteries to be integrated into the grid as part of a comprehensive strategy to reduce the environmental burden of electricity generation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jpowsour.2009.10.072.

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