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ARTICLE *in* ENVIRONMENTAL SCIENCE & TECHNOLOGY · APRIL 2015

Impact Factor: 5.33 · DOI: 10.1021/acs.est.5b01245 · Source: PubMed

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Field Assessment of the Village Green Project: An Autonomous Community Air Quality Monitoring System

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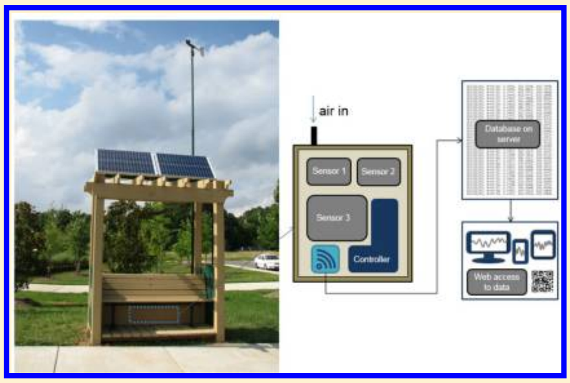
Supporting Information

ABSTRACT: Continuous, long-term, and time-resolved measurement of outdoor air pollution has been limited by logistical hurdles and resource constraints. Measuring air pollution in more places is desired to address community concerns regarding local air quality impacts related to proximate sources, to provide data in areas lacking regional air monitoring altogether, or to support environmental awareness and education. This study integrated commercially available technologies to create the Village Green Project (VGP), a durable, solar-powered air monitoring park bench that measures real-time ozone, $PM_{2.5}$, and meteorological parameters. The data are wirelessly transmitted via cellular modem to a server, where automated quality checks take place before data are provided to the public nearly instantaneously. Over 5500 h of data were successfully collected during the first ten months of pilot testing in Durham, North Carolina, with about 13 days (5.5%) of downtime because of low battery power. Additional data loss (4−14% depending on the measurement) was caused by infrequent wireless communication interruptions and instrument maintenance. The 94.5% operational time via solar power was within 1.5% of engineering calculations using historical solar data for the location. The performance of the VGP was evaluated by comparing the data to nearby air monitoring stations operating federal equivalent methods (FEM), which exhibited good agreement with the nearest benchmark FEMs for hourly ozone (r^2 = 0.79) and $PM_{2.5}$ (r^2 = 0.76).



1. INTRODUCTION

Air pollution is a common public health concern worldwide and for which access to data on local trends is highly desirable. Even in developed countries with well-established air quality measurement networks supporting regulations, recent findings on the spatial variability of air pollution[1−3] motivate research activities toward detecting air pollution on a finer geographic scale. Meanwhile, many populated areas of the world lack routine air quality measurement altogether. To date, the geographic coverage of monitoring networks has been limited due to the cost, infrastructure, and personnel requirements for air monitoring stations.

Air pollution measurement technology is undergoing rapid innovation toward systems that may increase the spatial and temporal resolution of observation data.[4] Whereas regulatory monitoring applications necessitates stringent requirements on measurement practices,[5] novel air measurement systems have been recently employed for other purposes such as the detection of local air quality trends in near-source environments, emissions characterization, and exposure assessment.[1−3,6,7] One area of development has been the acquisition of real-time air pollution data over large spatial areas using instrumented vehicles or hand-held devices.[6,8,9] Mobile measurement systems can generate high spatial-resolution data characterizing air pollution gradients; however, data collection is limited in duration due to the labor-intensive nature of mobile monitoring and can require sophisticated data processing to discern trends.[10] Another focus area for development has been stationary air measurement systems that can provide long-term data collection and are more easily deployed in community environments. The engineering challenge is maintain the collection of useful data while

Received: October 9, 2014
Revised: April 20, 2015
Accepted: April 23, 2015
Published: April 23, 2015

DOI: 10.1021/acs.est.5b01245
Environ. Sci. Technol. 2015, 49, 6085−6092

reducing physical size, power draw, maintenance frequency, and overall cost.

Low cost air sensors (e.g., under 2000 USD) for criteria pollutants (i.e., $PM_{2.5}$, ozone, carbon monoxide, nitrogen dioxide, sulfur dioxide) are undergoing rapid development, with envisioned applications for personal monitoring, incorporation into mobile measurement systems, and stationary sensor networks.[4] Recent field studies have demonstrated promising agreement with reference instruments in some cases;[11,12] however significant discrepancies have also been observed, particularly under variable environmental conditions.[13]

While the very low cost air sensors continue to be developed and tested, a number of commercially available air monitoring instruments exist at a midtier cost (e.g., 2000−8000 USD) that may enable the development of smaller and self-powered air measurement stations that could be deployed in communities for long-term observation of local air quality conditions. Utilizing instruments with on-board diagnostics to qualify their ongoing performance, these community stations may provide a midpoint between numerous very low cost sensors with greater risk for measurement error and the regulatory stations in limited number but with highly accurate data. The critical question is whether these instruments can provide reliable data over long time horizons under more challenging operational environments (lack of environmental conditioning, power fluctuations, and risk of vandalism) and limited operator intervention. EPA's Office of Research and Development recently undertook developing an integrated air and weather measurement system that is more easily deployed in community outdoor spaces, minimizes operator visits to maintain, and provides real-time, quality-checked data to the public. An additional goal was to create a flexible system that could be modified to include new technologies in the future.

This paper describes the Village Green Project (VGP) station design and investigates the system performance in terms of long-term operability, measurement accuracy compared with nearby reference stations, and feasibility for application in other locations.

2. METHODOLOGY

2.1. VGP System and Field Site Description. The design considerations for the VGP prototype included: (1) compact physical size and structural design supporting siting in community environments, (2) air pollution instruments enabling real-time data acquisition and quality assurance, (3) self-power and wireless communications infrastructure, and (4) commercial availability of components to enable technology transfer and system flexibility.

Figure 1. Photo of the installed station and schematic showing the system components (see Table 1 for component details). The artistic rendition of the bench was provided by Safeplay Systems.

The key components of the VGP system include air monitoring and weather instruments, power infrastructure, microprocessor, cellular modem, data server, and Web site. The hardware components are incorporated into a park bench structure to add value to a community environment (Figure 1). The selected instruments (Table 1) met several criteria, including producing real-time data (i.e., 1 min), low power draw, compact size, ancillary diagnostic data to support real-time quality checks, and requiring infrequent maintenance (e.g., one visit per three months). At the time of instrument selection, commercially available technologies meeting these stringent criteria were limited to a few pollutants ($PM_{2.5}$, ozone); however, future technology development may support an expanded variety of pollutants measured using a similar system design. The selected ozone instrument operates by UV absorption, while the $PM_{2.5}$ instrument operates by light scattering. The $PM_{2.5}$ instrument incorporates a humidity measurement to provide an optional artifact correction, which was activated during the field tests. The wind sensor is a traditional cup and vane measurement system, selected over an ultrasonic method as being more intuitive for community members and for its ability to be calibrated in a field setting if needed. Two solar panels with a rechargeable battery provide nearly continuous station operation based on available solar radiation. An Arduino microprocessor running on an open source coding language controls the system operation, including power management, data logging, and wireless data transmission. The microprocessor transmits the air pollution and meteorology readings every minute using a cellular modem to a receiving data server, where automated quality control checks are performed. During the field assessment period, the real-time quality-checked data were made available on a Web site for public access (www.airnow.gov/villagegreen). The entire system design, including Arduino code and quality checks, is available in Supporting Information. The overall design of the VGP prototype was intended primarily for research or other nonregulatory applications.

The physical structure of the prototype is a park bench made of recycled materials and has an integrated trunk that provides secure and weatherproof storage for the scientific instruments. After fabrication, the VGP prototype was installed in June, 2013 outside of a public library in Durham, North Carolina. To support this research study and additional outreach activities, a Memorandum of Understanding (MOU) was established between EPA and Durham County. The installation location was approximately 170 m north of an arterial roadway (NC-54) and 330 m south of a major interstate (I-40) highway. The bench was positioned for optimal winter sunlight, with solar panels facing south and oriented at a fixed tilt of 55 degrees.

2.2. Quality Assurance and Data Post-Processing. The measurement components of the VGP monitoring system generally function independently. If one instrument fails or becomes unavailable, the remaining measurement system will not be affected. For each 1 min data transmission, automatic screening were applied to check values of ancillary diagnostic variables (e.g., flow rate, cell pressure) that were reported for each instrument (Supporting Information). During the course

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Table 1. Major Components of Village Green Project System

no.	component (model)	manufacturer	power draw or supply loss (W)	sampling rate
1	$PM_{2.5}$ monitor (pDR-1500)	Thermo Scientific, Waltham, MA	2.0	1 min
2	ozone monitor (OEM-106)	2B Technologies, Boulder, Colorado	3.5	1 min
3	wind sensor (09101)	RM Young, Traverse City, Michigan	0.48	1 min
4	humidity and temperature sensor (HMP60)	Vaisala, Raleigh, NC	0.012	1 min
5	power controller (SunSaver SS-10L-12V)	Morningstar, Newtown, PA		n/a
6	absorbed glass mat (AGM) battery (Werker WKDC12-80P, 12 V, 80 Ah)	Batteries Plus, Green Bay, WI[a]	1.4 (estimated power supply loss) + 0.74 (relay, relay driver)	n/a
7	solar panel (SLP085-12MKCT 85 W, 12 VDC)	Solarland, Ontario, CA		n/a
8	microprocessor (Arduino Mega 2560)	Smart Projects, Italy[a]	1.2 (estimated)	n/a
9	cellular router (Airlink Raven XE)	Sierra Wireless, Carlsbad, CA	1.32	n/a
10	bench structure	Safeplay Systems, Marietta, GA	n/a	n/a

[a]Purchased through third-party supplier.

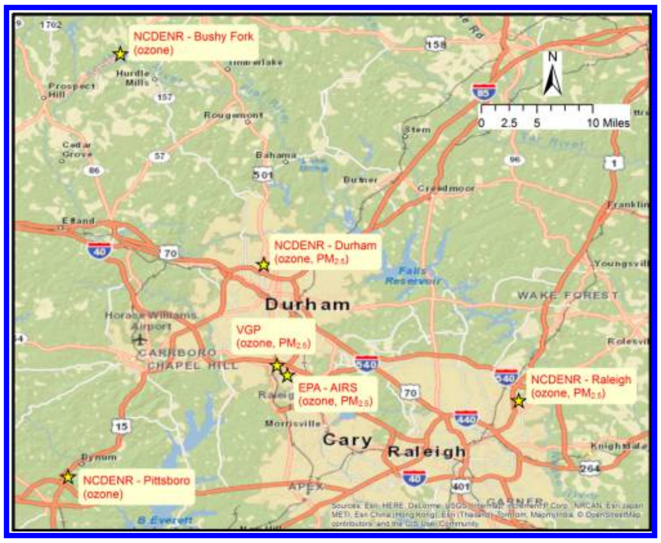

Figure 2. Location of VGP and nearby regulatory air monitoring sites.

of sampling, the only automated quality check adjusted and data reprocessed was related to the ozone instrument's lamp voltage, based upon manufacturer correspondence. An initially narrow tolerance on the lamp voltage (range of 0.6–2 V) as an automated data check screened out ozone data during cold temperatures. Although lamp's baseline voltage would decrease with temperature, the instrument measurement performance remained satisfactory. The raw ozone data stored locally on a memory card was reprocessed with a temperature conditional check (expanded range of 0.15–2 V during cold temperatures) prior to analysis. In addition to automated quality checks that were performed for each 1 min data transmission, additional manual checks were performed on each instrument prior to the initiation of measurements and then approximately every 90 days thereafter. Manual checks performed included flow and zero checks for the $PM_{2.5}$ instrument, flow, and multipoint calibration checks for the ozone instrument, and comparison against reference instruments for the temperature and relative humidity sensors. In addition, comparison with regional weather stations was conducted to verify wind speed and direction. It should be noted that the quality assurance measures conducted were from a viewpoint of the system being developed and applied for research purposes.

For analyses presented in this paper, postprocessing measures included averaging, as well as the application of a simple screening algorithm for the $PM_{2.5}$ data. While the site location is officially a nonsmoking environment, local exhaust events, such as incidental smoking or a vehicle idling near the bench, were suspected to cause infrequent brief spikes in $PM_{2.5}$ measurements. While no video monitoring was applied to identify the specific source, it was observed that during holiday periods when the library was closed, these sporadic spikes did not occur. To evaluate against nearby reference measurements, these infrequent outliers in $PM_{2.5}$ concentration due to presumed local exhaust were removed by flagging periods when the absolute concentration difference between sequential readings was greater than or equal to 15 $\mu g/m^3$. The rarity of these events resulted in only 0.32% of the data being flagged and isolated from analysis. The optical detection method is useful in providing a real-time $PM_{2.5}$ data over a wide dynamic range, whereas in this study the sporadic emission-related events were isolated from analysis for intercomparison purposes, other future applications may retain all data to characterize dynamic local trends.

2.3. Data Analysis and Comparison. Data were analyzed using an open-source statistical software R (http://www.r-project.org/) version 3.0.2 with "base", "openair", and "ggplot2" packages. To evaluate the VGP system operability, the system power status was summarized to assess the use of solar energy to support instrumentation operation. In addition, the feasibility of VGP operation was also determined through calculations of the system power draw against historic hourly solar radiation data from Typical Meteorological Year 3 (TMY3) for locations representing multiple latitudes in the continental United States.[14] To calculate the effect of possible variations in the power system design, the system operational time was estimated under scenarios of (1) addition of a second battery, (2) a 25% increase in solar panel size, and (3) the addition of a small (0.6 m diameter) wind turbine. These scenarios were selected considering potential modifications that would not increase the physical footprint of the station. Wind data incorporated into scenario (3) analyses was converted from the 10 m height wind speed of TMY3[14] to 5 m height (estimated wind turbine placement) wind speed based on vertical profiles of velocity in the suburban terrain.[15] It should be noted that actual wind turbine performance would depend on local meteorology at the installation location. In order to estimate system operation time, an algorithm (eq 1) was developed that incorporated the hourly power input, power draw-down by the instrumentation, battery storage capacity, and limits set by the system power controller (11.5–13.7 V) to

DOI: 10.1021/acs.est.5b01245
Environ. Sci. Technol. 2015, 49, 6085–6092

Table 2. VGP Operation Summary of Quality Checked Data

month	missing data per month (%): quality checks or maintenance: ozone	missing data per month (%): quality checks or maintenance: $PM_{2.5}$	missing data per month (%): low solar power	missing data per month (%): communication interruptions	overall completeness[a] (%): ozone	overall completeness[a] (%): $PM_{2.5}$	overall completeness[a] (%): wind	overall completeness[a] (%): temp/RH
2013/06	0	0	0	4	96	96	96	96
2013/07	0	0	0	7	93	93	93	93
2013/08	0	0	0	0	100	100	100	100
2013/09	0	1	0	0	100	99	100	100
2013/10	0	59	17	0	83[b]	24[b]	83	83
2013/11	0	1	3	31	66	65	66	66
2013/12	43	1	11	10	36[b]	79	79	79
2014/01	28	2	1	2	70[b]	96	97	97
2014/02	9	8	9	0	82	83	91	91
2014/03	8	4	3	6	83	87	91	91

[a]Completeness is the number of valid hourly concentration divided by the total hours per month. [b]Instrument removed temporarily for maintenance: pump replacement required for $PM_{2.5}$ instrument and ozone instrument was cleaned and recalibrated.

estimate the approximate state of charge (SOC) of the VGP battery for all hours in a year:

$$\mathrm{SOC} = \frac{Q_i}{Q_0} \tag{1}$$

where

$$Q_i = Q_{i-1} + \left(\int I_{\mathrm{in}}\, \mathrm{d}t - \int I_{\mathrm{out}}\, \mathrm{d}t\right)$$

$$I_{\mathrm{out}} = \frac{P_{\mathrm{load}}}{V_{\min}} = \frac{15\ \mathrm{W}}{11.5\ \mathrm{V}}\ \text{(maximum output current)}$$

$$I_{\mathrm{in}} = \frac{P_{\mathrm{in}}}{V_{\mathrm{float}}} = \frac{P_{\mathrm{sun}} + P_{\mathrm{wind}}}{V_{\mathrm{float}}} = \frac{P_{\mathrm{sun}} + P_{\mathrm{wind}}}{13.7\ \mathrm{V}}\ \text{(minimum input current)}$$

$$P_{\mathrm{sun}} = \frac{\mathrm{SR}_i}{1000} \times P_{\mathrm{rated}} \times \mathrm{PR}$$

SOC is the ratio between the battery capacity (Q_i in units of ampere-hour, Ah) and the rated capacity (Q_0 in units of Ah); typically, the battery works between a SOC from 0.2 to 1. For each hour, Q_i was estimated based on the battery capacity from the previous hour (Q_{i-1}), and the net capacity gain in this hour considering input power generation and system power consumption. The capacity (Q_i) was not allowed to exceed the rated capacity (Q_0) for a full battery. Since the current supplied to and output by the battery is dependent on the battery voltage, we created a conservative estimate of the power state by inputting values to the equation representing the extreme case of least input to and maximum output from the battery ($V_{\min}$ = 11.5 V, V_{float} = 13.7 V). Solar power generation was a function of hourly solar radiation for that specific location (SR_i, W/m^2), solar panel rated power (P_{rated}, W), and performance ratio (PR, assuming 75% for VGP). Wind power generation was estimated based on a polynomial relationship with wind speed from the wind turbine specifications (Supporting Information).[16] For any hour with a SOC less than 0.2, the VGP instrumentation is turned off. Thus, the total yearly VGP operational time could be estimated by counting the hours with SOC $\geq$ 0.2.

In addition, the VGP ozone and $PM_{2.5}$ data were compared against nearby reference stations. Located in a low-density suburban environment, the closest reference location (~1 mile from the VGP location) is the Air Innovation and Research site (AIRS), operated by the EPA on its campus in Durham, NC using Federal Equivalent Methods (FEMs) to generate 1 min readings of ozone, $PM_{2.5}$ and meteorological parameters. In addition, North Carolina Department of the Environment and Natural Resources (NCDENR) state monitoring locations are in the surrounding area (Figure 2, Supporting Information Table S-1).[17] The Raleigh station (17.9 miles from the VGP location) and Durham station (9.1 miles) each provide hourly $PM_{2.5}$ and ozone data, while the Pittsboro station (18.2 miles) and the Bushy Fork station (30.4 miles) report ambient ozone during ozone season (March−October). Specific FEMs used for comparison are noted in the Supporting Information.

Comparison with the AIRS site is emphasized over the NCDENR locations because of its very close proximity to the VGP station. Analyses include time series comparison, linear regression analysis, and investigation of any detectable measurement artifact in VGP ozone or $PM_{2.5}$ readings related to environmental conditions. Multiple linear regression models (eq 2) are used to correlate hourly VGP ozone and $PM_{2.5}$ concentration (C_{VGP}) to the corresponding AIRS concentration (C_{AIRS}) and meteorological variables of temperature (T) and humidity (RH).

$$C_{\mathrm{VGP}} = \beta_1 + \beta_2 C_{\mathrm{AIRS}} + \sum_{k=0}^{2} \beta_k x_k + \varepsilon \tag{2}$$

where β_1 is constant of regression, and β_2 and β_k are the regression coefficients, x_k is the ensemble of meteorological variables including temperature and relative humidity. To assess whether a temperature or humidity-related artifact exists, the regression was done stepwise to add the meteorological term in addition to the AIRS concentration variable. The values of the constant and coefficients are determined using the least-squares method which minimizes the error ε. The coefficient of determination (r^2) is used as the measure of goodness of fit.

DOI: 10.1021/acs.est.5b01245
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Table 3. Estimate of Annual VGP Power System Operation

U.S. city	latitude	original base design (%)	base plus second battery (%)	base plus solar panels 25% larger (%)	base plus small wind turbine (%)
Houston, TX	30.000	96.8	98.1	99.6	99.3
Raleigh-Durham, NC	35.867	93.6	94.9	97.8	96.7
Las Vegas, NV	36.083	98.9	99.9	100.0	100.0
New York, NY	40.650	87.4	88.6	92.3	97.0
Chicago, IL	41.983	86.2	87.5	92.0	94.5
Boston, MA	42.367	87.7	88.8	93.0	97.7
Seattle, WA	47.467	76.2	77.3	81.3	81.2

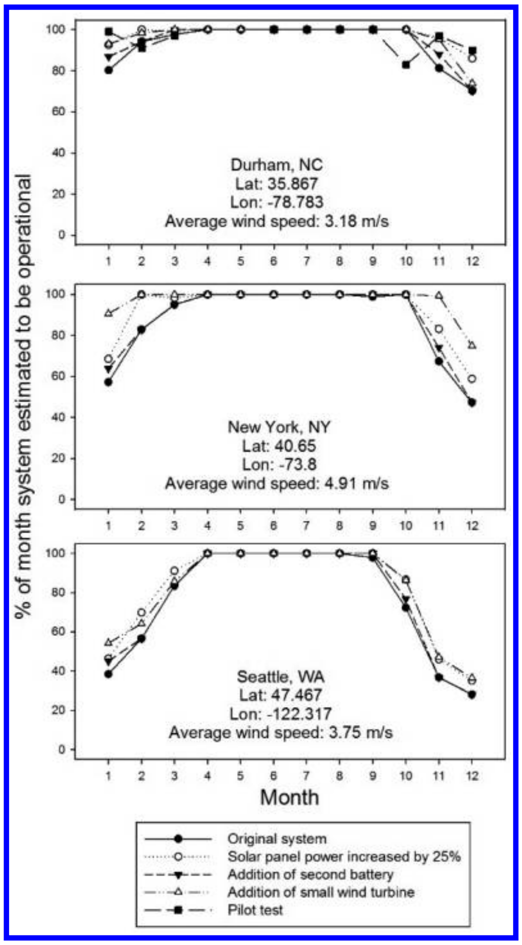

Figure 3. Estimated monthly power system operation for three U.S. cities. Calculations are conservative in assuming lowest input current and maximum output current. Several alternative scenarios are also shown, including increasing the size of the solar panels, adding a second battery, and adding a small wind turbine. Actual performance (pilot test) is shown for the Durham, NC location.

3. RESULTS AND DISCUSSION

3.1. VGP Operability. The original target for overall data completeness was set conservatively at 50%, considering the solar power system was minimized to the extent possible to keep a small physical footprint of the system and realizing the instruments may be challenged by extended field use without any environmental conditioning and frequent power cycling. If many more community environments could be measured with only 50% data completeness (e.g., near 100% data in the summer, partial data in the spring/fall, and some periods of extended downtime in the winter), that was considered an acceptable starting place from which technology development could continue improving. However, the actual performance of the VGP system significantly exceeded the conservative initial target (Table 2). In the first nine and half months of VGP operation from June 20, 2013 to March 31, 2014, the station successfully collected 5451 (80%) and 5536 (81%) hours of ozone and $PM_{2.5}$ concentration data, respectively. The system performed with highest overall data completeness during the summer to early fall. Communication interruptions were primarily due to EPA server maintenance or an error in the Arduino data transmission format, both of those issues were overcome through code improvements. In addition to power or communication issues causing data loss, infrequent instrument maintenance or technical issues led to additional data loss. Missing ozone data during December 2013 and January 2014 were primarily due to our investigation of low lamp voltage that was below our original quality check range (<0.6 V) under cold temperatures, which led to an updated temperature-conditional range for that variable based upon manufacturer correspondence. In addition, 2 weeks of $PM_{2.5}$ instrument downtime in October 2013 was due to an internal pump requiring replacement after one year of continual operation (including preliminary laboratory testing and subsequent field installation). Overall, despite several major winter storm events in North Carolina that provided reduced solar radiation during the winter of 2013−2014, the use of solar energy provided sufficient power to operate 94.5% of 10-month period, which translates to approximately 13.2 days down time. In addition, the instrumentation withstood an ambient temperature range of −14 to 34 °C without interruption in sampling. It should be noted that the internal heat created by the operating instrumentation provided an approximate 10 °C gain in temperature over ambient conditions within the instrument enclosure.

To assess the operability of VGP stations in different latitudes, we selected several locations within the United States, including the Durham, NC testing site, to estimate how the VGP system would function in terms of sufficient power to fully operate. Engineering calculations utilizing available solar radiation data predicted 93.6% operation time using the base design in Durham, NC (Table 3). Both the annual estimate and monthly calculated values (Figure 3) closely compare with actual field observations of solar power system performance. In addition, several potential design variations, adding a second battery, increasing the solar panel size, or adding a small wind turbine, were estimated to increase the system operation time to be over 98%. Predictions of system performance in other cities shows the original base design providing >85% operation time for latitudes up to ∼42 degrees North (Boston, MA, Chicago, IL) (Table 3). However, predicted power loss during the winter time increases, as shown for New York City (Figure 3). Going further north, the base design of the system has decreased overall operational time and greater seasonal swings. Another consideration not fully explored here would be additional power loss related to snow or ice temporarily blocking sunlight from reaching the solar panels.

3.2. Comparisons with Regulatory Air Monitoring Stations: Ozone. The hourly VGP ozone measurements closely tracked the AIRS site ozone readings (example in Figure 4), averaging 4.4 ppb or 18% higher hourly concentrations compared to AIRS data. Linear regression of the hourly VGP ozone measurements over the entire ten month study period

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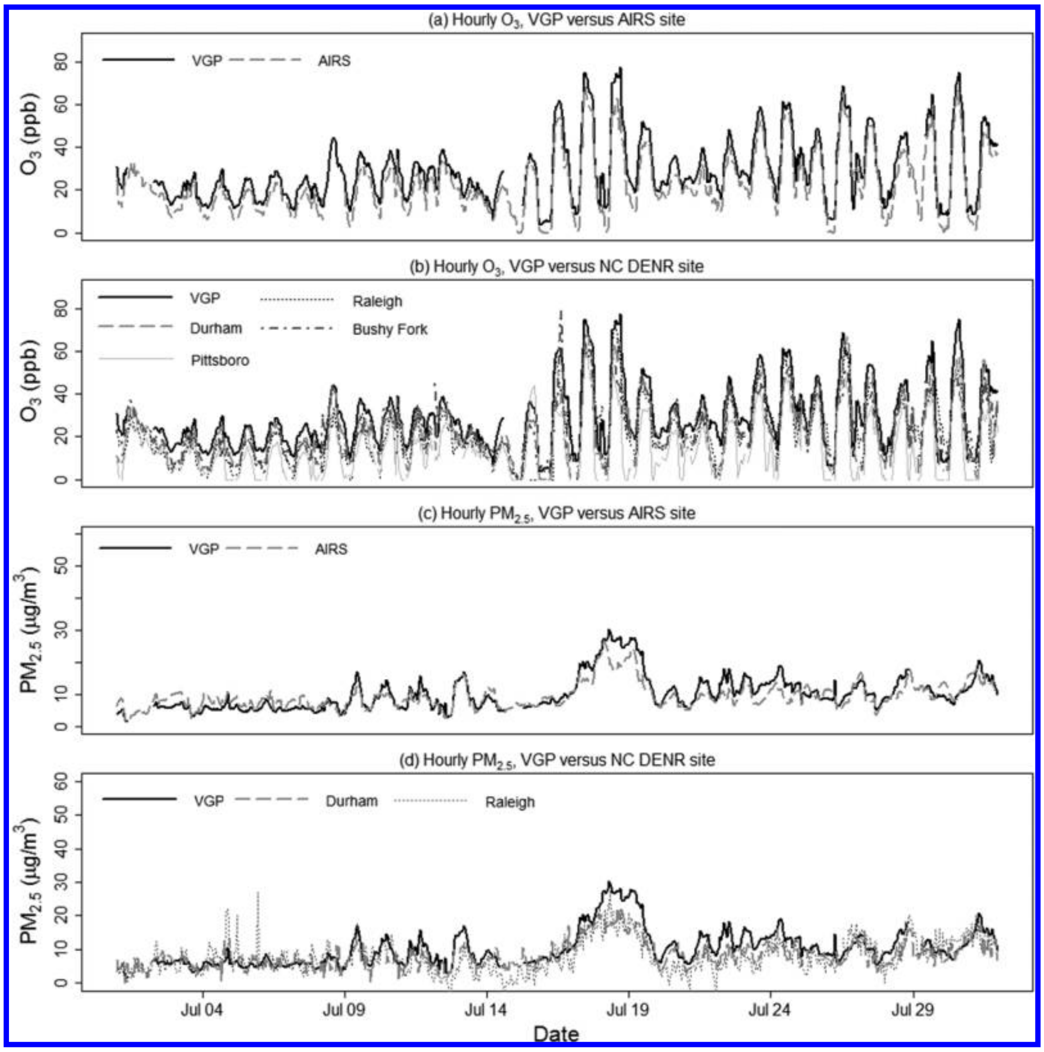

Figure 4. Example time series (July, 2013) of VGP and regulatory ambient air monitoring sites measurements.

demonstrates strong correlation at hourly time interval (r^2 = 0.79) with AIRS measurements (Figure 5). Comparing with NCDENR ambient monitoring sites, a strong correlation between measurements were also observed, but the relationship decreased with distance to the VGP station; r^2 of linear regression of hourly O_3 measurements between VGP and two Triangle area sites, Durham and Raleigh, were 0.74 and 0.65, respectively. For the other two rural sites that only operate from March to October (Pittsboro and Bushy Fork), correlations were lower with r^2 of 0.58 and 0.59, respectively. The Pittsboro site consistently reported the lowest O_3 concentration among all sites compared.

3.3. Comparisons with Regulatory Air Monitoring Stations: $PM_{2.5}$. The VGP $PM_{2.5}$ measurements generally showed good agreement with AIRS data (Figure 4). On average, the hourly average $PM_{2.5}$ concentration of VGP station during the 10-month was about 1.0 $\mu g/m^3$ or 10.2% less than that of the AIRS site. A linear regression analysis between the screened VGP $PM_{2.5}$ measurements and the reference AIRS measurements yields strong agreement (r^2 = 0.76, Figure 5) at an hourly averaging period. In order to understand whether local traffic emissions on the surrounding roads affect the comparison with AIRS, the correlation was repeated for only night-time hours (8 PM to 6 AM), revealing a modestly improved correlation (r^2 = 0.81). Comparison of hourly $PM_{2.5}$ concentrations (all hours) with DENR sites located further away revealed moderate agreement (Figure 4), with the linear regression r^2 of about 0.56 with the closer Durham site and 0.31 with the Raleigh site for the hourly data (Figure 5). One additional factor that may contribute to the lower Raleigh location correlation is the FEM monitor type, which may have greater measurement noise at shorter averaging intervals (Supporting Information Table S-1). The strong to moderate correlation between VGP versus reference stations indicated the area-wide covariation in $PM_{2.5}$ concentrations in this suburban setting, however the effect of local emissions is also evident as the correlation coefficient is reduced with distance.

3.4. Effects of Temperature and Relative Humidity. To minimize power consumption, the VGP system design provided no controlled environmental conditions to the instruments. Therefore, it is of interest to explore whether fluctuating temperature or humidity impact the $PM_{2.5}$ and ozone measurements. Linear regression models were employed to investigate whether environmental factors caused measurement bias. During the ten-month period, hourly ambient temperature varied from −14 to 34 °C, while relative humidity varied from 12% to 100%. Applying multiple linear models to VGP ozone and $PM_{2.5}$ concentrations (eq 2), separately, statistically significant relationships ($p < 0.01$) were found for most derived coefficients (Table 4). For ozone, adding

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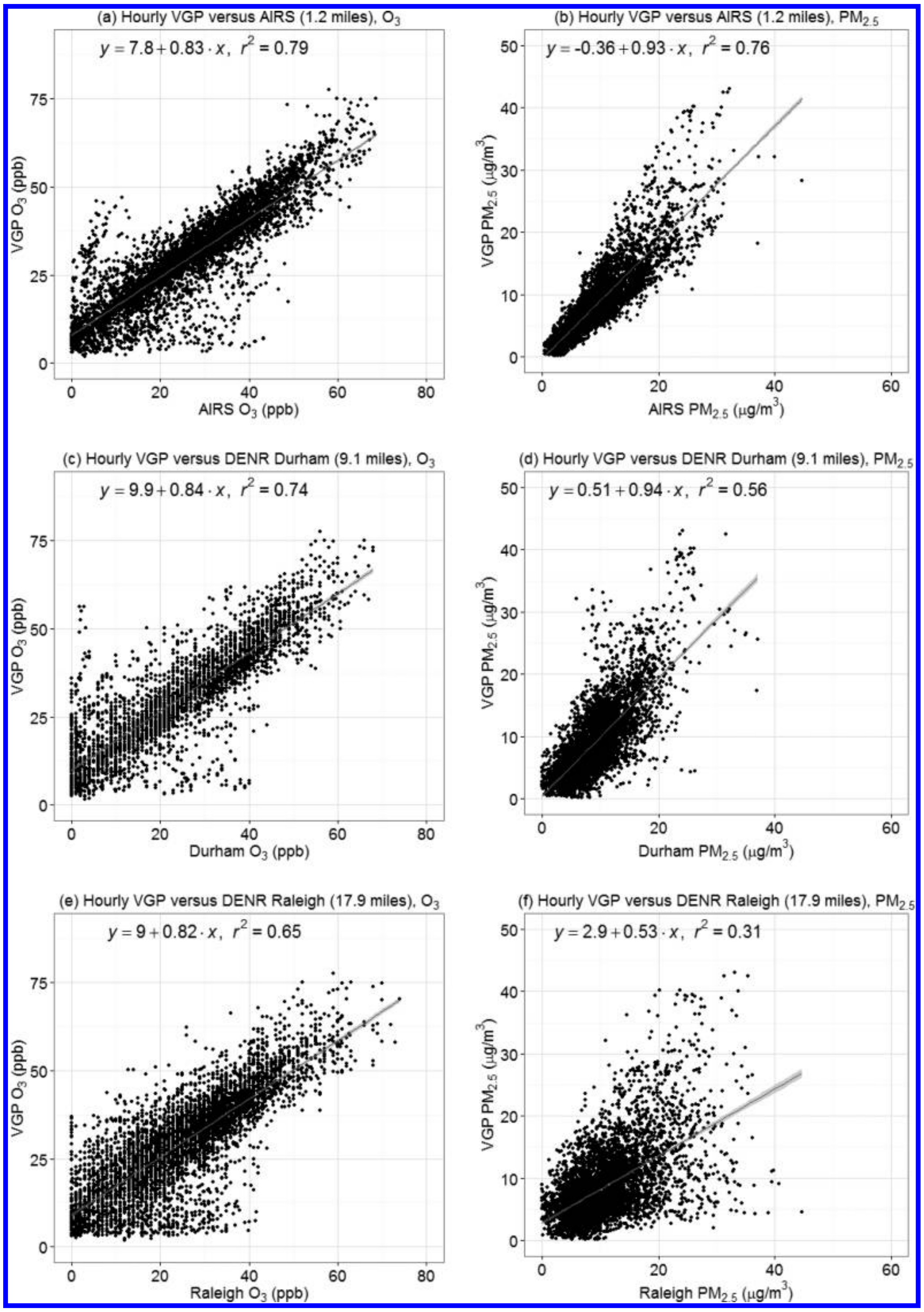

Figure 5. Correlations between VGP and AIRS, Durham and Raleigh FEMs for hourly average ozone and $PM_{2.5}$ concentration during the study period.

meteorological terms to the equation in addition to the AIRS concentration term caused only a slight change in the r^2, indicating a negligible artifact on VGP ozone concentrations related to environmental conditions. For $PM_{2.5}$, the added humidity term did not improve correlation, which indicates that the on-board compensation for relative humidity sufficiently corrected for the known artifact. Adding the temperature term slightly improved the $PM_{2.5}$ model fit by an increase of 6% in r^2. Overall, the maximum change in r^2 for ozone, including all factors, was an increase from 0.79 to 0.81, whereas the $PM_{2.5}$ r^2 changed from 0.76 to 0.82. In both cases, the results suggest that environmental conditions only modestly affect the measurements.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Six tables and 24 figures that supplement the main paper, including detailed design documents of the Village Green Project prototype. The Supporting Information is available free

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Table 4. Multiple Linear Regression Models of Hourly Village Green Project (VGP) Against AIRS Concentrations, Ambient Temperature, and Relative Humidity

			coefficient								
			constant		C_{AIRS}		RH		T		
C_{VGP}	variables	N^b	estimate	SE[c]	estimate	SE[c]	estimate	SE[c]	estimate	SE[c]	adjusted r^2
ozone	C_{AIRS}	5409	7.81[a]	0.17	0.83[a]	0.01					0.79
	C_{AIRS}, RH	5314	5.53[a]	0.54	0.85[a]	0.01	0.02[a]	0.01			0.79
	C_{AIRS}, T	5314	5.71[a]	0.19	0.80[a]	0.01			0.18[a]	0.01	0.81
	C_{AIRS}, RH, T	5314	7.04[a]	0.52	0.78[a]	0.01	−0.02[a]	0.01	0.18[a]	0.01	0.81
$PM_{2.5}$	C_{AIRS}	4850	−0.36[a]	0.09	0.93[a]	0.01					0.76
	C_{AIRS}, RH	4755	−0.37	0.15	0.93[a]	0.01	0.00[d]	0.00			0.75
	C_{AIRS}, T	4755	−2.22[a]	0.09	0.90[a]	0.01			0.14[a]	0.00	0.82
	C_{AIRS}, RH, T	4755	−1.84[a]	0.13	0.91[a]	0.01	−0.01[a]	0.00	0.14[a]	0.00	0.82

[a]Statistical significant at $p < 0.01$. [b]Sample size. [c]Standard error. [d]Not statistically significant ($p > 0.05$).

of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01245.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The Village Green Project would not have been possible without many helping hands, including student services contractors Katie Lubinsky, Rachel Clark, and Dana Buchbinder, EPA staff including Solomon Ricks, Ann Brown, Kelly Leovic, Scott Moore, Renee Marshall, John Masters, Emily Snyder, Vasu Kilaru, Eben Thoma, Emily Smith, Robert Wright, Paul Groff, Richard Shores, Doug McKinney, Frank Princiotta, Tim Watkins, Dan Costa, Jewel Morris, Ann Vega, and Jacques Kapuscinski; Durham County Library, NC staff including Tammy Baggett, Sandra Lovely, Tamera Anderson, Jennifer Brannen and Kathleen Hayes; ARCADIS staff including Drew Knott and Aaron DeBlois; CGI staff including Mike Tumbarello, David Crawford, Stephen Jackson, and Becky Taylor; Mike Strub with SafePlay Systems, and Jim Mosteller with Mosteller Design. Comparison regulatory data from NCDENR is also much appreciated.

■ REFERENCES

(1) Baldauf, R.; Thoma, E.; Hays, M.; Shores, R.; Kinsey, J.; Gullett, B.; Kimbrough, S.; Isakov, V.; Long, T.; Snow, R.; Khlystov, A.; Weinstein, J.; Chen, F. L.; Seila, R.; Olson, D.; Gilmour, I.; Cho, S. H.; Watkins, N.; Rowley, P.; Bang, J. Traffic and meteorological impacts on near-road air quality: Summary of methods and trends from the Raleigh near-road study. *J. Air Waste Manage. Assoc.* **2008**, *58* (7), 865−878.

(2) Hagler, G. S. W.; Baldauf, R. W.; Thoma, E. D.; Long, T. R.; Snow, R. F.; Kinsey, J. S.; Oudejans, L.; Gullett, B. K. Traffic and meteorological impacts on near-road air quality: Summary of methods and trends from the Raleigh near-road study. *Atmos. Environ.* **2009**, *43* (6), 1229−1234.

(3) Kimbrough, S.; Baldauf, R. W.; Hagler, G. S. W.; Shores, R. C.; Mitchell, W.; Whitaker, D. A.; Croghan, C. W.; Vallero, D. A. Long-term continuous measurement of near-road air pollution in Las Vegas: Seasonal variability in traffic emissions impact on local air quality. *Air Qual., Atmos. Health* **2013**, *6* (1), 295−305.

(4) Snyder, E. G.; Watkins, T. H.; Solomon, P. A.; Thoma, E. D.; Williams, R. W.; Hagler, G. S. W.; Shelow, D.; Hindin, D. A.; Kilaru, V. J.; Preuss, P. W. The changing paradigm of air pollution monitoring. *Environ. Sci. Technol.* **2013**, *47* (20), 11369−11377.

(5) Hall, E.; Kaushik, S.; Vanderpool, R.; Duvall, R.; Beaver, M.; Long, R.; Solomon, P. Integrating sensor monitoring technology into the current air pollution regulatory support paradigm: Practical considerations. *Am. J. Environ. Eng.* **2014**, *4* (6), 147−154.

(6) Elen, B.; Peters, J.; Van Poppel, M.; Bleux, N.; Theunis, J.; Reggente, M.; Standaert, A. The Aeroflex: A bicycle for mobile air quality measurements. *Sensors* **2013**, *13* (1), 221−240.

(7) Williams, R.; Rea, A.; Vette, A.; Croghan, C.; Whitaker, D.; Stevens, C.; McDow, S.; Fortmann, R.; Sheldon, L.; Wilson, H.; Thornburg, J.; Phillips, M.; Lawless, P.; Rodes, C.; Daughtrey, H. The design and field implementation of the Detroit Exposure and Aerosol Research Study. *J. Exposure Sci. Environ. Epidemiol.* **2009**, *19* (7), 643−659.

(8) Hagler, G. S. W.; Thoma, E. D.; Baldauf, R. W. High-resolution mobile monitoring of carbon monoxide and ultrafine particle concentrations in a near-road environment. *J. Air Waste Manage. Assoc.* **2010**, *60* (3), 328−336.

(9) Jiao, W.; Frey, H. C. Comparison of fine particulate matter and carbon monoxide exposure concentrations for selected transportation modes. *Transp. Res. Rec* **2014**, *2428*, 54−62.

(10) Brantley, H. L.; Hagler, G. S. W.; Kimbrough, E. S.; Williams, R. W.; Mukerjee, S.; Neas, L. M. Mobile air monitoring data-processing strategies and effects on spatial air pollution trends. *Atmos. Meas. Tech.* **2014**, *7* (7), 2169−2183.

(11) Holstius, D. M.; Pillarisetti, A.; Smith, K. R.; Seto, E. Field calibrations of a low-cost aerosol sensor at a regulatory monitoring site in California. *Atmos. Meas. Tech.* **2014**, *7* (4), 1121−1131.

(12) Gao, M.; Cao, J.; Seto, E. A distributed network of low-cost continuous reading sensors to measure spatiotemporal variations of PM2.5 in Xi'an, China. *Environ. Pollut.* **2015**, *199*, 56−65.

(13) Williams, R.; Long, R.; Beaver, M.; Kaufman, A.; Zeiger, F.; Heimbinder, M.; Heng, I.; Yap, R.; Acharya, B.; Grinwald, B.; Kupcho, K.; Robinson, S.; Zaouak, O.; Aubert, B.; Hannigan, M.; Piedhrahita, R.; Masson, N.; Moran, B.; Rook, M.; Heppner, P.; Cogar, C.; Nikzad, N.; Griswold, W. *Sensor Evaluation Report*, EPA/600/R-14/143; US Environmental Protection Agency: Research Triangle Park, NC, 2014.

(14) National Solar Radiation Data Base 1991−2005 Update: Typical Meteorological Year 3. http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/ (accessed 2015/01/02).

(15) Crasto, G. *Numerical Simulations of the Atmospheric Boundary Layer*; Università di Cagliari: Cagliari, Italy, 2007.

(16) The 60W 12V Marlec Rutland 504 Windcharger Specification Sheet. http://www.absak.com/pdf/WG504Espec.pdf (accessed 2015/01/02).

(17) NC Division of Air Quality Current Monitoring Data by Site. http://daq.state.nc.us/ambient/monitors/ (accessed 2014/12/12).

DOI: 10.1021/acs.est.5b01245
Environ. Sci. Technol. 2015, 49, 6085−6092