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Climate Change and Environment in the Arab World

January 2013

Effect of distributed electric power generation on household exposure to airborne carcinogens in Beirut

Alan Shihadeh, Marc Al Helou, Najat Saliba, Sara Jaber, Nader Alaeddine, Elias Ibrahim, Zahra Salahieh, Maher Chiit

Research Study Report

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The Climate Change and Environment in the Arab world Program aims to understand the climate change and environment policy process in the region and define the most appropriate policy recommendations by linking development in applied sciences on issues related to climate change and environment to social sciences.

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Rabih Mahmassani	*Communications Manager*
Donna Rajeh	*Designer*

Alan Shihadeh, Marc Al Helou, Najat Saliba,
Sara Jaber, Nader Alaeddine, Elias Ibrahim,
Zahra Salahieh, Maher Chiit

Published by the Issam Fares Institute for Public Policy and International Affairs, American University of Beirut.

This report can be obtained from the Issam Fares Institute for Public Policy and International Affairs office at the American University of Beirut or can be downloaded from the following website: www.aub.edu.lb/ifi

Beirut, December 2012

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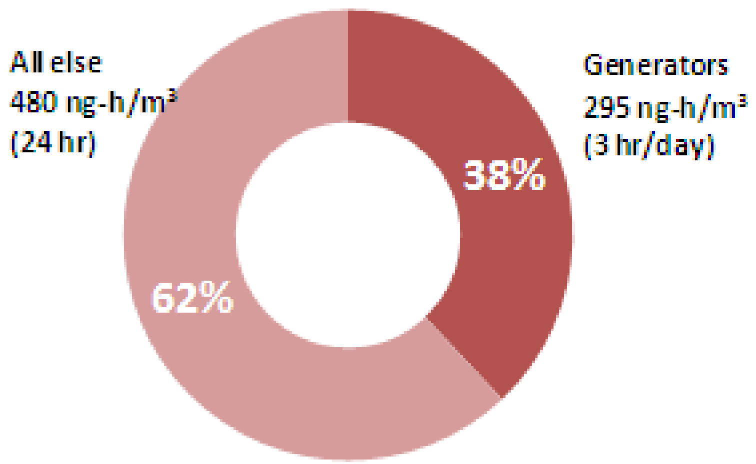
Summary

Due to inadequate power production capacity, EDL has in recent years instituted a rotating power outage regimen in Lebanon. People and businesses have turned to privately-owned diesel generator sets for power during outages. Because these generators are located in dense urban areas, their emissions may significantly increase inhalation exposure to harmful substances.

In this study, levels of airborne carcinogens were measured when diesel generators were operating and when they were off, on the balconies of 20 residences located in the Hamra area of Beirut. Data were interpreted using a computational fluid dynamics model of pollutant dispersion.

The study found that the use of diesel generators for only 3 hours per day accounted for 38% of the daily carcinogen exposure in the Hamra area of Beirut. This represents an increased exposure of approximately 60% over the background levels had no generators been present. The added carcinogen exposure from diesel generators is similar to that of smoking a few cigarettes per day, and would be significantly higher in areas where EDL power is cut for more than 3 hours per day.

The decrepit state of the electric power sector in Lebanon, in addition to other problems, is likely resulting in deteriorating health of the population in the near and long term. Immediate remedial measures are warranted.



Introduction

In Lebanon as in many other countries of the global South, environmental regulations are lax or laxly enforced. In recent years, the Electricite du Liban (EDL) has been implementing a rotating power outage regimen to balance limited production capacity with consumer demand. Depending on the geographic area, outages vary from 3 hours to more than 12 hours per day. To continue to use electricity when the national supply is interrupted, households and businesses have returned to civil war era micro power generation– at city block, building level, or individual consumer scales. This private electric power sector is dominated by diesel generator sets running on high sulfur fuel. In high socio-economic status areas, it is common to find a diesel generator in every building, while in mid- to low-socioeconomic status areas, neighborhood-level power producers sell subscriptions to individual households or businesses. While it is illegal for independent power producers to sell power, the practice is unofficially tolerated given the inability of EDL to meet demand. Typically rated below 500 kVA[1], and therefore exempt from Lebanese pollutant emission regulations, generators are installed in open parking lots, on sidewalks, in building basements, over building entrances, and on ground-level building service areas. Their stack exhaust heights are also unregulated and can be found at any height ranging from ground level to the top of the nearest building.

The generators typically operate inside or directly abutting residential buildings, in areas characterized by a dense, vertical urban morphology where air circulates poorly and pollutants can accumulate. Because diesel engine emissions are toxic and carcinogenic and exposure to diesel exhaust is associated with heart and lung disease, neurological and developmental disorders in children, and a variety of cancers, the high density of diesel generator sets near places of residence and work in Lebanon raises the question whether the decrepit state of Lebanon's electric power sector presents a significant public health concern through inhalation exposure of combustion fumes. In this project, we were concerned with elucidating whether diesel generators contribute significantly to the budget of inhaled carcinogen exposure in Beirut, a city whose yearly average ambient particulate matter concentration (PM2.5) exceeds WHO guidelines by approximately 100%. To do so, we measured concentrations of airborne carcinogen levels where people live and work, while monitoring the operation of nearby diesel generators. We hypothesized that an elevation of airborne pollutant concentrations would be observed whenever diesel generators were operating, and that this pattern would be invariant with respect to other factors (e.g. time of day, weather conditions, location).

1 Decree 8/1 (2001) addresses emissions from electrical generators. Operators of generators larger than 500 kVA will be in compliance with the law if either the stack reaches a minimum specified height or the stack emissions of CO, NO, and SO2 are below specified limits. There are no regulations for generators 500 kVA or smaller.

METHODS

The work described in this report involved conducting a neighborhood survey of diesel generator sets, measuring airborne carcinogens and the state of electric power (on grid/off grid), and interpreting these measurements using a fluid mechanics-based model of pollutant transport in urban areas.

Study area. The study area (Fig1) was located in Beirut's Hamra neighborhood near the American University of Beirut, and was bounded by Sidani (N), Hamra (S), Omar bin Abdul Aziz (E), and Sadat (W) streets. The overall length x width of this area is approximately 575 m x 195 m. This relatively high socio-economic status area contains a mix of residential and commercial buildings, and it experiences scheduled power outages of 3 hours per day between the hours of 6 am and 6 pm. The outage schedule is divided into four zones, and a particular building in the Hamra area may fall into any one of these depending on which power line feeds it. The layout of the underground power lines is such that adjacent buildings often fall in different time zones.

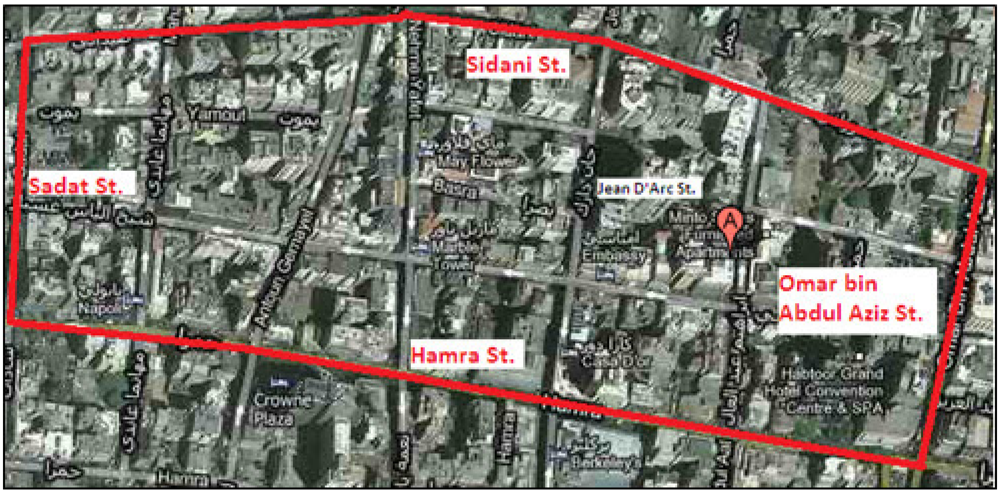


Figure 1. Satellite photo of survey area (Google Maps)

Survey method. During the 2-month period starting November 1, 2010, study personnel walked through the neighborhood and systematically identified every building in the study area, using satellite images obtained from Google Maps™ as a guide. Each building was assigned a number, and each was visited to document if and how it obtains electric power during scheduled outages. Normally this involved interviewing the building doorman or owner, and inspecting the generator set in the building. Some buildings required several visits before the doorman or owner could be located. Interviewees were asked to provide the following information: engine rating (kVA), fuel consumption rate (L/month), year of installation, power outage time zone, and how the engine is maintained. The engine exhaust stack was traced visually to the outlet, and the outlet height was estimated by noting the floor at which it exhausted and assuming an average elevation of 3 m per floor. Survey reliability was assessed by comparing results for an overlapping survey area assigned to different study personnel. Blinding was used to minimize study bias.

Ambient pollutant measurement system. A sampling system was devised to enable continuous measurement of airborne carcinogen concentration (particle-bound poly aromatic hydrocarbons, PPAH) while monitoring interruptions in the electric power supply. The system enabled direct observation of changes in ambient PPAH concentration whenever diesel generators went on or off, allowing for apportionment of ambient PPAH levels to diesel generators. The system was packaged in two weather proof boxes, and was designed to run unattended for 10 days at a time. The major components of this system were an Ecochem PAS 2000 PPAH monitor, an analog relay circuit that outputs a DC voltage signal whenever electric power is interrupted, and a data logger to digitally record minute-by-minute readings of the PAS 2000 and the relay circuit output. Because power is interrupted whenever a building is switched to/from the national grid to a local power generator, the signal of the relay circuit indicates the period during which anearby diesel generator is operating. Illustrative results from a 24 hour period at one sampling location are shown in Figure 2, where the vertical red lines indicate the first and second power interruption during the period, corresponding to when the diesel generator went on and then off. An uninterruptable power supply module was developed to run the system for up to 6 hours without external power. In addition, a particle sampling train was built into the sampling system. The sampling train consisted of a vacuum pump, glass fiber filter assembly, and electronic flow meter. The vacuum pump drew a known amount of ambient air through the filter, which in turn trapped all airborne particles passing through it. We used this sampling train to verify that the PAS 2000 was sensitive to changes in ambient PAH levels. In particular, the average reading of the PAS 2000 over each 2 week sampling period was compared to the results obtained by extracting the particles trapped on the filter and analyzing the extract using GC-MS. The PAS 2000 reading average should correlate linearly with extracted PAH.

Measurement campaign. We deployed the system on the balconies of 19 residences occupied by AUB personnel who volunteered for the study, as well as one day care location. At each location, the system was installed for approximately 2 weeks. Of these 20 sites, 19 were located in the Hamra neighborhood adjacent to AUB (Figure 3), and one was located in Rabieh. The sampling campaign took place between January 2010 and January 2012, and approximately 330 24-hour sampling periods were recorded.

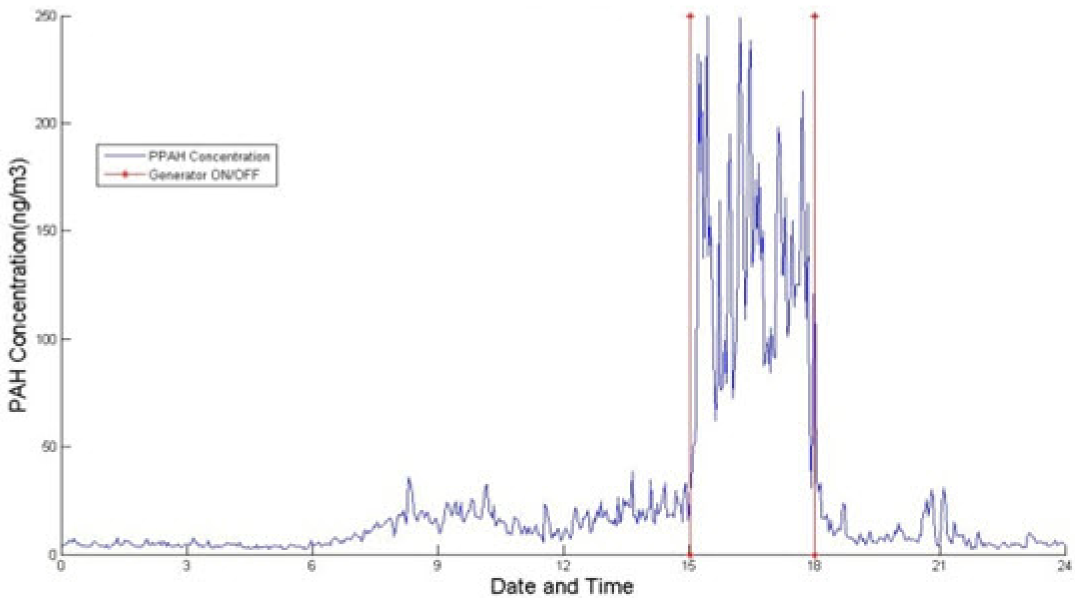


Figure 2. Ambient PPAH concentration measured during a single 24 hour period at one sampling site. PPAH levels are seen to spike when a nearby electric generator was operating. Generator start/stop are indicated by the vertical red lines.

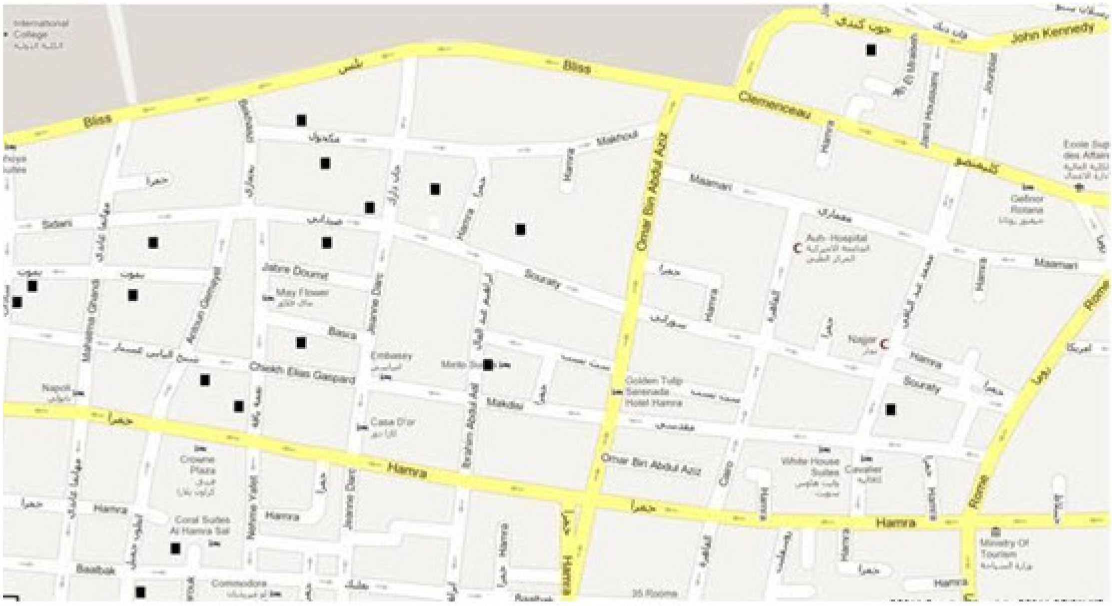


Figure 3. Sampling locations in Hamra area of Beirut (indicated by black filled rectangles).

Analysis. We sought to elucidate the attributable fraction, AF, of PPAH exposure to the use of diesel generators. Exposure is defined as the area under the concentration versus time curve, and the AF is defined here as the fraction of daily exposure that derives from diesel generators. Because there are other sources of PPAH concurrent with the generator sets (e.g. automotive emissions), computing the attributable fraction required some assumptions. We approached this problem by computing the "baseline AF", and the "dispersion-adjusted AF". The baseline AF was computed by assuming that only the building's own generator (and others operating concurrently) affects the ambient PPAH concentration. In other words, all generators that operate at times other than those of the building where the measurement is taking place are assumed to be far enough away that they do not impact ambient PPAH levels. To compute the baseline AF from the time series data of PPAH, it is assumed that had there been no generator, the ambient concentration during the 3 hour power outage episode would have been the average of the ambient concentrations measured 30 minutes prior to and 30 minutes after the episode. Calculating baseline AF is therefore straightforward, but it neglects contributions of generators operating on other schedules to the total PPAH budget. Baseline AF can be considered a lower bound for the AF.

To account for effects of generators operating in other time zones, the dispersion-adjusted AF,is computed using computational fluid dynamics (QUIC-PLUME, Lawrence Livermore Labs) to simulate transient 3-dimensional flow fields around buildings in the study area, and to simulate particle pollutant trajectories. Building outer dimensions and locations were obtained from drawings obtained from the Lebanese Army. Based on the trajectories and knowledge of the distribution of diesel generators and hourly wind conditions in the study area, we were able to compute the "radius of impact", the radial distance from a given location (i.e. a balcony on which measurements are made) in which a diesel generator could impact the ambient pollutant concentration. Using a map provided by EDL of the electric power distribution network of the study area (Fig 4), and load shedding schedules by electrical sub-station, we were able to compute the relative contributions of diesel generators operating on various time zones within a given radius of impact. Using the average values obtained after thousands of simulations in which the measurement location was randomly varied within the study area, we are able to relate measured PPAH concentrations to the background concentrations resulting from everything other than diesel generators. We found the average radius of impact to be 210 m.Further details can be found in Helou (2012).

RESULTS

Survey. We identified a total of 184 buildings and 109 diesel generators in the study area. Figure 5 below illustrates the locations, reported fuel consumption, and generator size found in the survey. Approximately 15% of the generators exhausted at ground level, with the majority of the balance exhausting at roof height. Total installed capacity amounted to 15,000 kVA, with an average generator size of 137 kVA. Total reported diesel fuel consumption rate amounted to 136,500 L/month, corresponding to a fuel bill of approximately $120,000/month. Assuming an average fuel-electricity conversion efficiency of 25%, and a cost of electricity of 0.13/ kWh, the equivalent energy could have been purchased from EDL for approximately $44,000/month, resulting in a net loss of $76,000/month in the survey area. It should be emphasized that this estimate only includes the cost of fuel; including other direct costs such as maintenance and capital outlays, and indirect costs due to health effects would make the losses significantly larger.

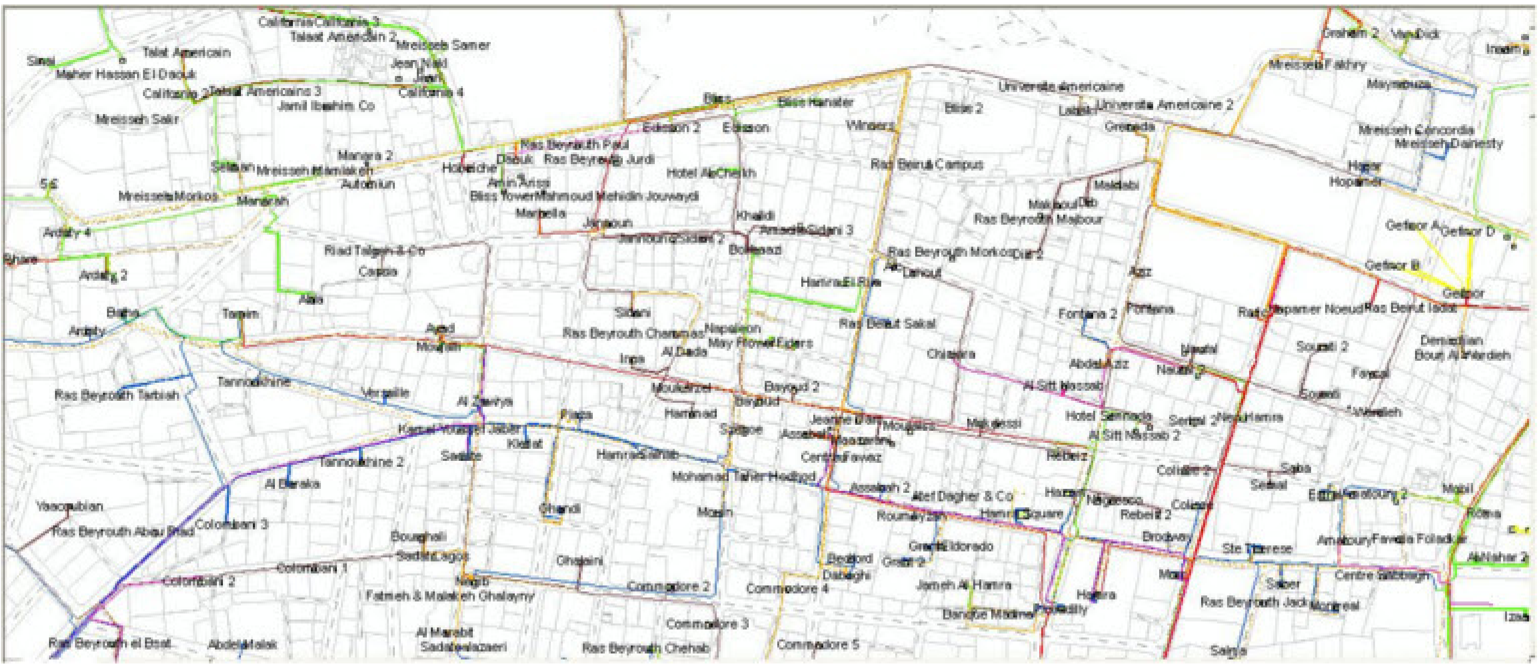


Figure 4.Electrical power network, colored by substation line. (Provided by EDL)

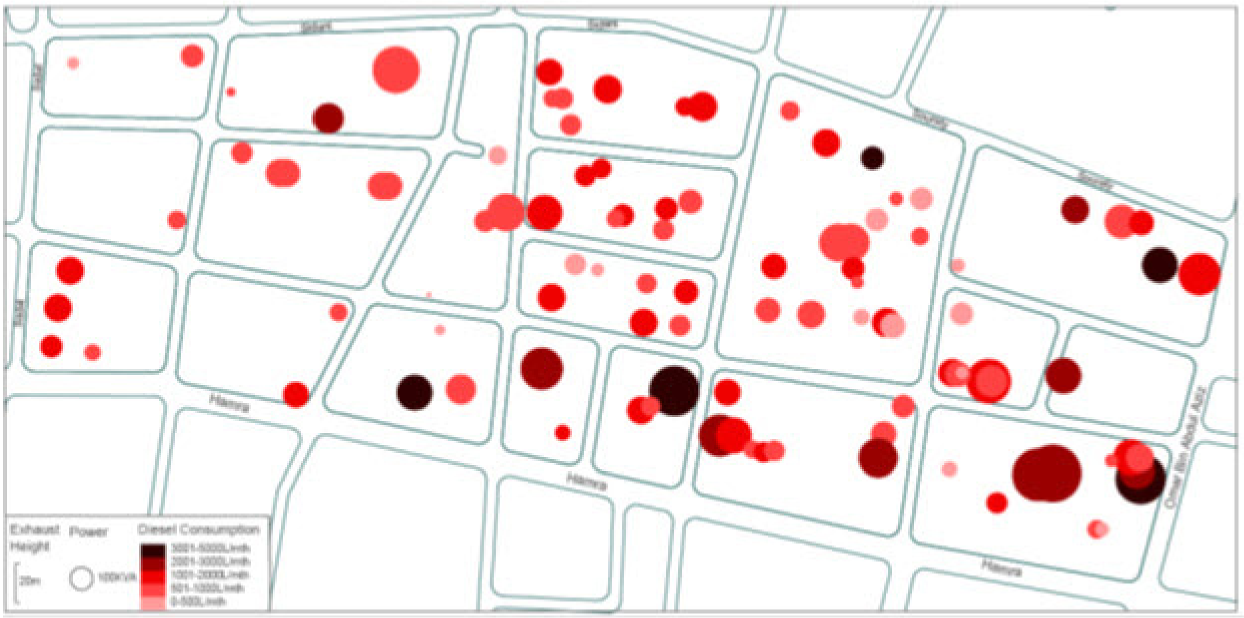


Figure 5. Diesel generator survey results by location, size, and fuel consumption.

Power outage schedule

Consistent with EDL's published rationing schedule, power outages in the Hamra area were found to occur between 6 am and 6 pm, for duration of approximately 3 hours (2.8±0.19 hrmean±stdev). Also consistent with the published schedule, the outage timing rotated by day in the following order: 3-6 pm, 12-3 pm, 9 am-12 pm, 6-9 am.

Ambient PPAH concentrations

PPAH concentrations were found to rise considerably whenever the power was interrupted. Figure X below shows the average ambient PPAH concentration during power outages and when power was being delivered. The data shown are for 6 am to 6 pm during each sampling day. When averaged across all sites, the average PPAH concentration during power outages was 73 ng/cm3, compared to 35 ng/m3 when EDL power was being delivered at the sampling location.

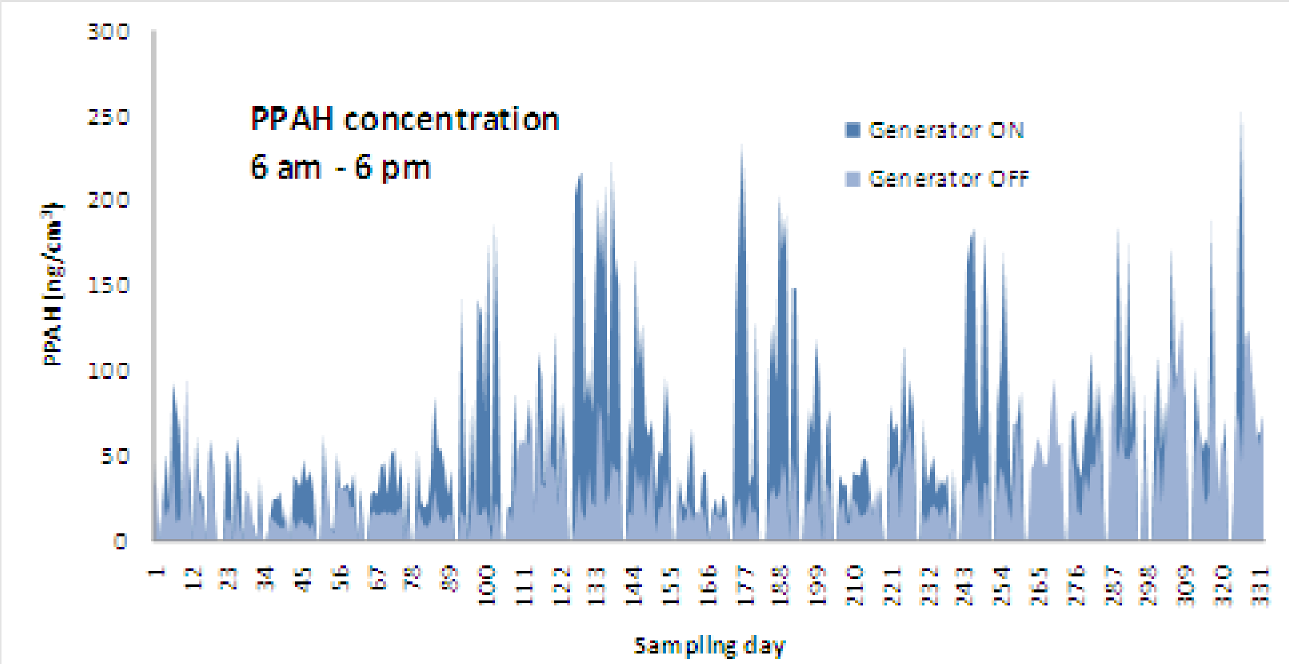


Figure 6. Average PPAH concentration during 3 hour power outage and 9 hour remainder in the hours 6 am – 6 pm for each sampling day. This chart illustrates the difference in ambient PPAH during power rationing and non-rationed periods each day.

Another perspective can be obtained by averaging minute-by-minute PPAH concentrations across all days and sampling sites, to obtain an "average 24 hour day" in Hamra. The result is shown in Fig 7 below (blue line), where it can be seen that the period from 6 am to 6 pm is greatly elevated over other times of the day. The rapid rise in ambient PPAH at 6 am is attributable to both electric generators and morning traffic, at a time when the atmosphere is stable and wind is minimal. Also shown (in red) is the ambient PPAH concentration when the 3 hour periods during which the power is rationed are excluded. The latter represents what the ambient PPAH would be if diesel generators in the local time zone had remained off, while all other generators (i.e. those in other time zones) operated normally. It can be seen that simply removing the effects of generators in the immediate vicinity of a given residence would significantly reduce PPAH levels. Thus, even without detailed analysis, it is clear that diesel generators contribute significantly to the ambient pollutant budget. To quantify this contribution, we turn now to the attributable fraction (AF).

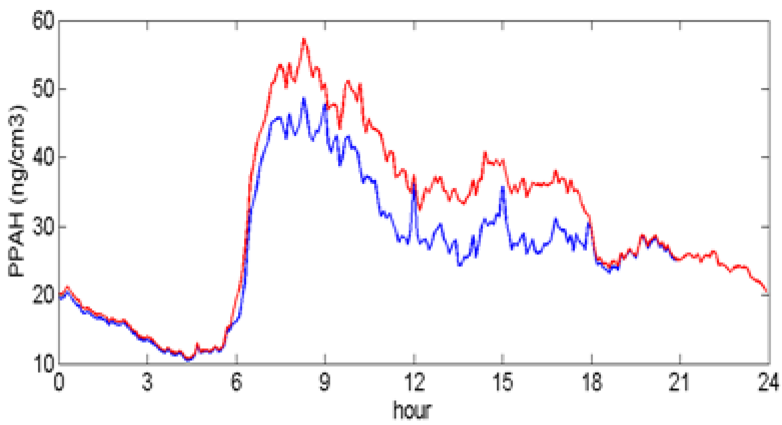


Figure 7.PPAH concentrations during an "average day" in the survey area. Red line corresponds to raw data, while blue line corresponds to data obtained when 3 hour power outage periods are eliminated. The blue line includes contributions of the urban background as well as diesel generators which are operating on other time schedules than that of the sampling site. Blue line therefore indicates ambient concentration if power were never interrupted at the sampling site.

Attributable fraction

Mean PPAH concentrations during measured during local power outage ($C_{g,l}$) and other time zone power outages ($C_{g,o}$) and the 24-hour average background PPAH concentration (C_b) were computed as outlined in the Methods section above. The background concentration represents the 24-hour average effect of all sources other than diesel generators. Thus daily exposure to PPAH due to non-generator background sources is given by Eb = 24 C_b. Similarly, exposure due to generators operating in the local 3 hour power outage window is calculated as Eg,l = 3 ($C_{g,l}$-C_b), while that due to other generators is given by $E_{g,o}$ = 9 ($C_{g,o}$-C_b). The numerical results are given in Table 1 below.

	Mean concentration ng/m^3	Resulting daily exposure ng-h/m^3
Background (24 hrs)	20	480
Local generators (3 hrs)	73	160
Other generators (9 hrs)	35	135
		Total 775

Table 1.PPAH concentrations in background (i.e. all sources other than generators), during local power outage, and during power outages in other time zones than the local generator (in the hours 6 am-6 pm).

The attributable fraction of ambient PPAH to private diesel generators is therefore (135+160)/775 = 38%, as shown in Figure 8.

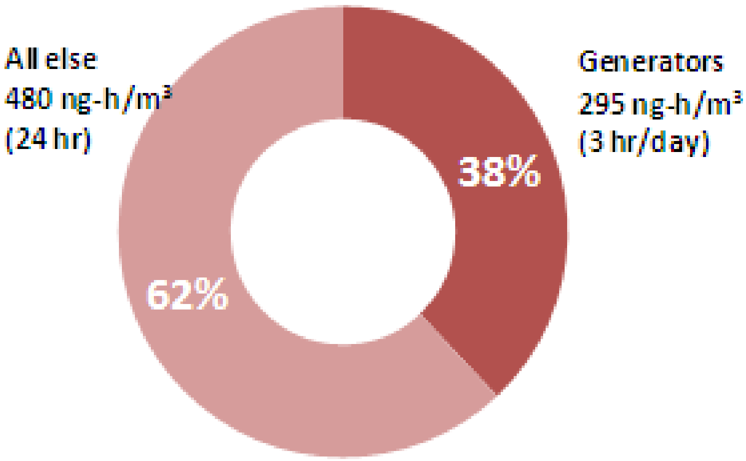


Figure 8.Attributable fraction of ambient PPAH concentration to diesel generator operation in Hamra, Beirut.

DISCUSSION

Privately owned diesel generators account for approximately 40% of airborne PPAH in the Hamra area of Beirut, despite the fact that they only operate for 3 hours/day. Areas in which diesel generators operate for longer than 3 hours/day can be expected to have proportionally higher ambient concentrations. It is therefore clear that current use of private generators to meet electricity demand during power rationing periods is leading to significantly higher airborne pollution levels and inhalation exposure to carcinogenic compounds.

While these findings warrant a detailed analysis of health effects, some perspective can be given now. A particularly notorious component of PPAH is benzo(a)pyrene, BaP.BaP was identified decades ago as a complete carcinogen – a compound capable of inducing tumors without need for contributions from other chemicals – and as the major causative agent in tobacco smoke induced lung cancer. By analyzing our filter samples, we found that BaP was well correlated with the PPAH measurement, with a calibration factor of 7.5 ngBaP/mg PPAH reported by the PAS2000 instrument. Using an estimated air inhalation of 14 m3/day for a person living in Hamra, an inhaled dose of benzo(a) pyreneof 121ng/day is estimated from breathing outdoor air. Of this, 46ng are due to private electric generators. By comparison, a single cigarette delivers an inhaled dose of 20-40 ng of benzo(a)pyrene. Thus in areas where generators operate for 12 hours/day, inhaled doses of BaP can approach the equivalent of half a pack of cigarettes/day.

This study adds impetus to the need for addressing Lebanon's chronic electric power shortages.

References

Al Helou, Marc (2012). Impact of distributed urban generators on household exposure to carcinogenic airborne particles during rolling blackout episodes. Master of Engineering Thesis, Mechanical Engineering Department, AUB.

The Issam Fares Institute for Public Policy and International Affairs (IFI)

American University of Beirut | PO Box 11-0236, Riad El Solh 1107 2020, Beirut, Lebanon
Tel: +961-1-374374, Ext: 4150 | Fax: +961-1-737627 | Email: ifi@aub.edu.lb | Website: www.aub.edu.lb/ifi