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Article

Tracking Electrification in Vietnam Using Nighttime Lights

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Abstract: We report on a systematic ground-based validation of DMSP-OLS night lights imagery to detect rural electrification in Vietnam. Based on an original survey of village-level units in Vietnam, this study compares nighttime light output from the U.S. Air Force Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) against ground-based survey data on electrical infrastructure and electricity use in 200 electrified villages. Monthly and annual composites record a one-point increase in brightness along DMSP-OLS's 63-point brightness scale for every 60–70 additional streetlights or 240–270 electrified homes. Using a time series of 90 nightly images, the data show a one-point increase in brightness for every 125–200 additional streetlights, or 550–700 additional electrified homes. The results highlight the potential to use night lights imagery to support efforts to connect the 1.2 billion people who lack electricity around the world.

Keywords: night lights; electricity; Vietnam; ground-truth

1. Introduction

Nighttime lights have long been recognized as a valuable indicator of the availability and use of electricity around the world. Studies show that nighttime light output strongly correlates with electricity generating capacity and economic activity at the regional and national levels [1–8]. Yet there remains little knowledge of how well nighttime satellite imagery detects the use of electricity in rural settings across the developing world, particularly at the level of individual villages and small towns [9].

Rural areas in developing economies are important because they are where modern energy sources are in shortest supply. Of the 1.3 billion people estimated to lack access to electricity around the world, more than 99% reside in the developing world, and most live in rural areas [10]. The ability to track and monitor patterns of electricity use in rural regions thus represents an important application of nighttime satellite image analysis. This paper provides the first systematic evaluation of Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) night lights imagery to detect the use of electricity at the village level in Vietnam.

Vietnam has experienced a dramatic increase in electrification in recent decades. The share of households with electricity access has grown from 2.5 percent in 1975 to 96 percent by 2009. Through a remarkable effort, the country with the assistance of international financial institutions has succeeded in providing access to more than 80 million people over 33 years; the number of people with access to electricity grew from 1.2 million in 1976 to about 82 million in 2009 [11–13]. According to the World Bank Development Indicators, average electricity consumption in Vietnam in 2011 was 1073 kWh per person, at an average per capita income of $4510. The level of consumption is far higher than in our earlier study sites: in Senegal, power consumption was 187 kWh per capita and only around 35 kWh per capita in Mali at levels of income of $2140 and $1590 respectively. The level of electricity consumption in Vietnam is similar to that of more developed countries like Ecuador (1192 kWh/capita; $9420 income/capita) and Peru (1248 kWh/capita; $9950 income/capita) in Latin America. Meanwhile, electricity consumption in Vietnam is far higher per person than in India (683 kWh/capita; $4840 income/capita) and Pakistan (449 kWh/capita; $4450 income/capita).

A key motivation for conducting this study in Vietnam is to evaluate the properties of nighttime satellite data in detecting electricity use in a country with relatively robust electricity usage, widespread household access to electricity, and relatively consistent power service with few power outages. This is important since it enables us to mostly rule out variations in the quality and reliability of the power grid on the ground as we seek to better understand variability in (DMSP-OLS) nightly data across the developing world [1,14–16].

This current work extends upon prior research validating the use of night lights to detect electricity usage in Senegal and Mali in western Africa. In that study, the first of its kind, our project team collected ground-based survey and global positioning system (GPS) data from 232 villages in Senegal and Mali in 2011 and compared information on local electricity use to brightness levels recorded in nighttime satellite imagery from DMSP-OLS [9]. The results showed that electrified villages are consistently brighter than unelectrified villages across a variety of nighttime satellite images produced at annual, monthly, and nightly frequencies. Based on information drawn from the surveys, we found that electrified villages appear brighter in satellite imagery because of the presence of streetlights, and brightness increases with the number of streetlights. In contrast, the correlation between light output recorded by the satellite with household electricity use and access is low, presumably because electricity use is very rudimentary in many village homes. These results were meaningful because they demonstrate that nighttime satellite imagery can reliably detect the use of electricity even in underdeveloped rural settings with very basic electrical infrastructure and usage patterns.

For this current study, our project team collaborated with the Vietnam Institute of Energy to collect official data on electricity usage in Vietnam's 68 province-level units as well as to conduct original surveys in 200 villages and towns across the country in August and September 2013. Specifically, we selected locations or villages at the third administrative subdivision level, often referred to as the commune-level subdivision. As of 2010, there were slightly more than 11,000 commune-level subdivisions in Vietnam. The goal of the surveys was to collect detailed information on the use of electricity in villages, including data on the number of streetlights, electrified households, and electrified public facilities. We also recorded information on demographic and socioeconomic characteristics in each village. Using handheld GPS devices, surveyors recorded the geographic coordinates on the periphery of each village to enable estimates of its geographic size. Finally, surveyors recorded the coordinates of the brightest location in each village (typically a main street or public square) to enable spatial joining with nighttime satellite imagery.

In parallel, we collected corresponding DMSP-OLS imagery over 90 nights spanning the dates of our survey collection, as well as the relevant monthly composites and the closest annual composite produced by the National Geophysical Data Center at the National Oceanic and Atmospheric Administration (NOAA).

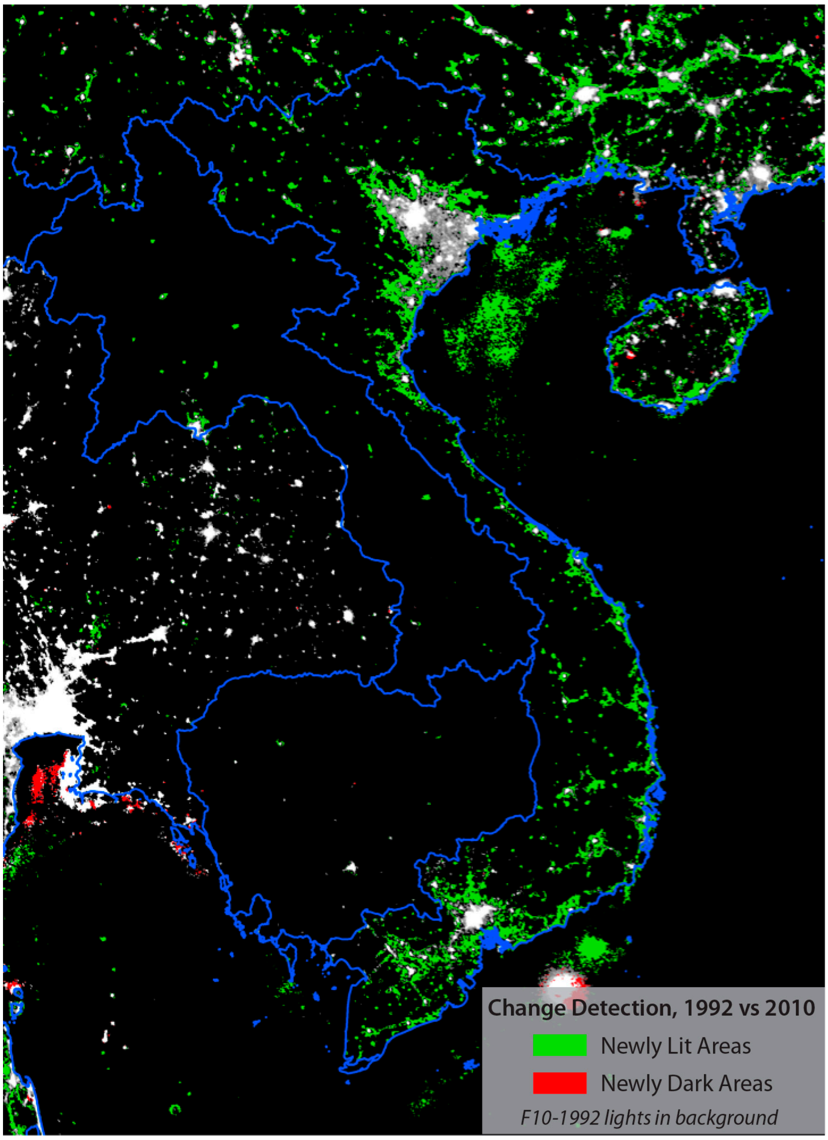
This paper presents our key findings from Vietnam:

- Electricity consumption at the province level is highly correlated with the level of nighttime light emission. Increases in brightness are largely explained by growth in residential sector electricity consumption, which significantly contributes to the evening peak demand in many countries. At the province level, a one percent increase in residential electricity consumption is associated with a 0.62% increase in nighttime brightness along DMSP-OLS's 63-point brightness scale.
- The emission of light from electrified villages is distinct and clearly visible in nighttime satellite imagery collected by the DMSP-OLS satellite.
- The observed brightness of electrified villages is a function of the number of electrified homes and the number of streetlights. This relationship holds across a range of statistical models and across nightly, monthly, and annual imagery sources.
- Processed satellite data in the form of monthly or annual composites record a one-point increase in brightness for every 60–70 additional streetlights or 240–270 electrified homes. Raw nightly data are accompanied by higher levels of noise and thus are not widely used to monitor electricity service provision. Using a time series of 90 nightly images captured over three months and with only basic additional filtering, our methods were able to detect a one-point increase in brightness for every 125–200 additional streetlights, or 550–700 additional electrified homes.
- Even villages with no public outdoor lights emit significant levels of light output, indicating significant use of lighting (and leakage of light) in domestic and commercial electricity use. This further corroborates the 2008 IEG study "The Welfare Impact of Rural Electrification: A Reassessment of the Costs and Benefits", which states that "the dominant use of electricity in rural households is lighting" [12].

2. Study Area and Data

Electricity consumption in Vietnam has increased rapidly in recent decades. Nighttime satellite imagery provides visual evidence corroborating these notable accomplishments. Figure 1 is a change detection image comparing average time stable night lights in 1992 and 2010, as produced by NOAA's National Geophysical Data Center. Green areas show the outcomes of electrical grid expansion and rural electrification programs, highlighting places that were dark in the 1992 image but appear lit in 2010, while red areas are places that have become dark over the same timeframe. Overall, the image captures a considerable increase in the spread and coverage of electricity provision over the last two decades in Vietnam.

Figure 1. Change in nighttime lights in Vietnam, 1992 *vs.* 2010. Source: Image and data processing by the National Oceanic and Atmospheric Administration (NOAA)'s National Geophysical Data Center. Defense Meteorological Satellite Program (DMSP) data collected by the US Air Force Weather Agency.



Since the 1970s, satellites from the U.S. Air Force Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) have flown in polar orbit capturing high-resolution images of the entire earth every day and night [17]. From an altitude of 830 km above the earth, these images reveal concentrations of outdoor lights, fires, and gas flares at a fine resolution of 0.56 km. On-board averaging of 5 by 5 blocks of fine data produces "smoothed" data with a nominal spatial resolution of

2.7 km. Most data are made available in the smooth spatial resolution mode. While its original purpose was to detect clouds using moonlight, it also was able to detect lights from human settlements, fires, gas flares, heavily lit fishing boats, lightning, and the aurora.

Early images from the DMSP-OLS were recorded on film strips, limiting their usefulness to most scholars. Beginning in 1992, digitized data began to be archived at the NOAA National Geophysical Data Center, facilitating their analysis and use by the scientific community. The subset of nighttime imagery captured in the late evening hours provide an unusually rich perspective on human activity, as it reveals the use of electricity for outdoor lighting. To date, the primary data products used by most scientists are a series of annual composite images created by NOAA-NGDC. These are created by overlaying all images captured between 20:00 and 21:30 local time during a calendar year, dropping images where lights are shrouded by cloud cover or overpowered by the aurora or solar glare, and removing ephemeral lights like fires and other visual noise. The result is a series of composite images of annual time stable night lights covering the globe for each year from 1992 to 2009 [5,6,18]. While the processing to create time stable annual composites creates a very useful product, the screening process to remove pixels with ephemeral light output may be a constraint on efforts to detect electricity provision in rural areas of the developing world where electricity access is known to be subject to erratic power outages and planned load shedding.

Images are scaled onto a geo-referenced 30 arc-second grid (approximately 1 km^2 at the equator). The brightness of each pixel is encoded with a digital number on a relative 6-bit scale from 0 to 63. These are relative values and are affected by the gain settings on the image capture device. The gain levels are set automatically on-board the satellite and are not recorded in the data stream. As a result, variations in pixel brightness values over a series of nightly images can result from changes in gain settings as well as changes in light-generating activities on the ground. Increasing the number of nightly images used in analysis may help reduce potential biases from gain setting fluctuations.

Technically, the low-light sensing capabilities of the OLS permit the detection of radiances down to 10^{-9} W/cm^2/sr/μm. In practice, cloud cover, solar glare, atmospheric disturbances, and sensor noise significantly affect the quality of any single image, making it difficult to establish what kinds of human-generated light output are detectable in practice. Some prior research has documented that the DMSP sensors can capture concentrated light output from very small areas, including U.S. towns with populations as low as 130 people [18].

In the developing world, however, little research exists to document whether night-time satellite imagery can reliably detect electrification. While cities and large towns are easy to detect because of the overall intensity and concentration of outdoor lighting, it is not known whether satellite imagery can reliably detect electricity availability and use in smaller village settings.

The challenge is heightened by technical limitations on the satellite sensor which do not enable it to detect low levels of light output. Especially in the developing world, rural electrification is characterized by low power loads distributed across small numbers of users, and often dispersed widely across space. An electrified village might not be detectable simply because it does not generate enough light output at night to be detectable by the sensor. Moreover, rural electrification is implemented differently across the developing world. Electrified villages may or may not have outdoor street lighting, and when they do, streetlights are often dim using lower luminosity designs.

Our research investigates these concerns by directly comparing luminosity levels observed by satellite imagery against detailed data on the level, extent, and intensity of electricity usage in rural communities in a developing country. This is an important context in which to study the properties of nighttime satellite imagery since improving access in rural regions in the developing world is a priority for many electrification agencies and international development partners. With improved insights on the properties of nighttime satellite imagery in village settings, such data may be able to facilitate the monitoring of service stability and power cuts to rural communities, the tracking of progress in the expansion of service to remote regions, and the identification of potentially overlooked or lagging communities and regions in a country's rural electrification plans.

3. Methods and Results

To first establish the relationship between night lights and electricity consumption, we compare satellite measures of light output against official data on electricity consumption. The most disaggregated level for which consumption data are reported is at the province level, the second-level administrative unit in Vietnam. The country's main power utility company, EVN, reports total electricity consumption at the province level in each year from 2000 to 2010. For each year, we also computed the total brightness of each province from the corresponding annual composite imagery of time stable night lights. This was done by summing the brightness levels of each 30 arcsecond pixel located within the boundaries of each province, using boundary shapefiles from the FAO's Global Administrative Unit Layers (GAUL) project.

Figure 2 plots the relationship between electricity consumption reported by the power company against total brightness measured by satellite for each of Vietnam's 68 province-level units in each year. Each of the correlations are statistically significant and positive with a Pearson's correlation coefficient ranging from 0.77 to 0.92, indicating that satellite imagery provides a reliable measure of the intensity of electricity use in Vietnam. Across all 680 observations over the time series, the two measures correlate at a level of 0.85 with a p-value of less than 0.001, evidence of a clear positive relationship between electricity use and total brightness observed from space. Overall, these results indicate that satellite data provide a reliable and valid indicator of electricity consumption at the sub-national level.

In six of the years (2004, 2005, 2009, 2010, 2011, and 2012), the EVN data includes information on the sectoral composition of electricity consumption, allowing us to explore how brightness of a province at night is separately related to electricity usage in the residential, commercial, industrial, and agricultural sectors. Table 1 below shows parameter estimates from a multi-level ordinary least squares regression on province brightness with province and year fixed effects. The omitted category in the regression is electricity usage in other sectors. The results are almost identical when industry or agriculture is the omitted category.

The specification of this "within" model allows us to estimate how changes in each sector's electricity use within each province is related to changes in brightness in that same province over time. The results indicate that nighttime brightness is most closely related to increases in power use in the residential sector. This is consistent with the observation that in many countries, residential consumption significantly influences peak electricity demand in the evening hours. This is an important result since it shows that observed changes in brightness in satellite data are likely to be related to changes in electricity usage by households. Since the variables are logged values, the coefficients can be interpreted as brightness elasticities: a one percent increase in a province's residential electricity consumption is associated with a 0.62 percent increase in nighttime brightness along the DMSP-OLS's relative scale. There is some evidence that increases in commercial electricity use are also associated with higher brightness, but the effect is not statistically significant. Growth in industrial and agricultural electricity use is not associated with changes in brightness, which is plausible since outdoor illumination is not a primary feature of power usage in these sectors.

To further study the relationship between electricity use and nighttime light output in Vietnam at an even more disaggregated level, our project team administered surveys in 200 village-level units across Vietnam. The villages were drawn from seven provinces representing a range of geographic and economic conditions. The surveys were administered by trained staff from the Vietnam Institute of Energy from 26 August to 25 September 2013.

Figure 2. Nighttime brightness and electricity consumption in 68 Vietnam provinces, 2000–2012.

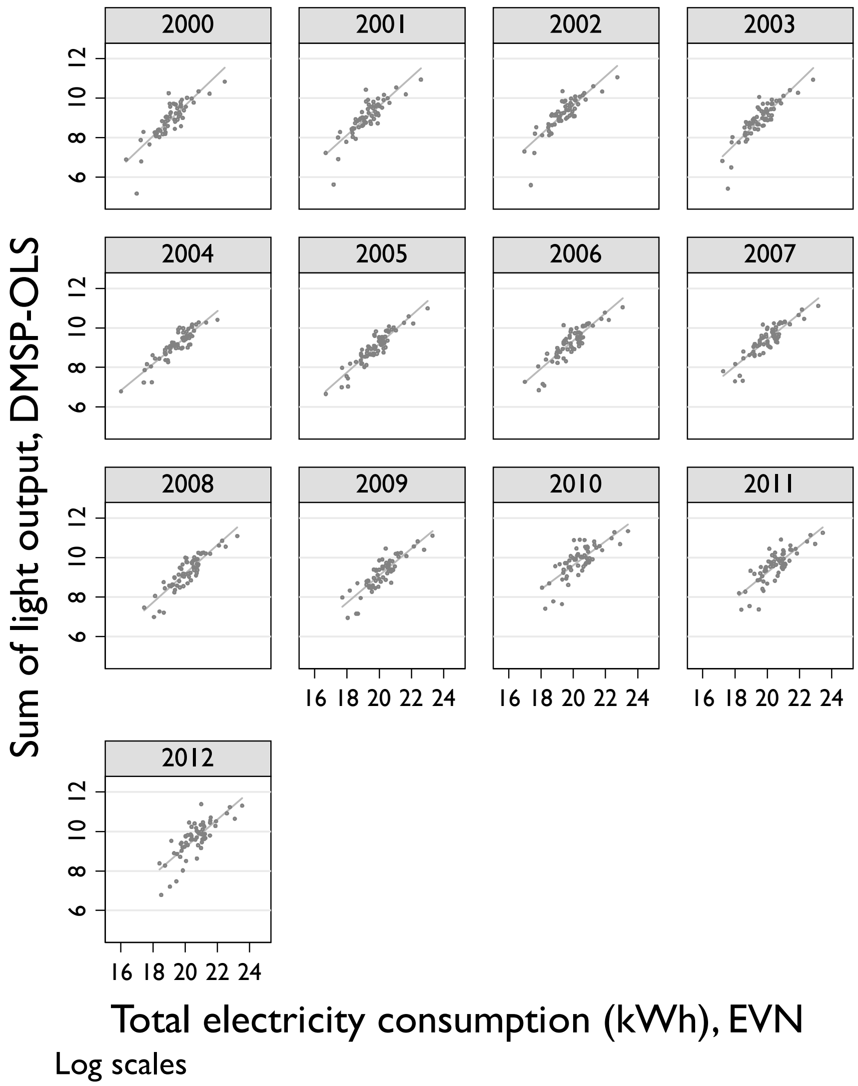


Table 1. Sectoral determinants of province brightness.

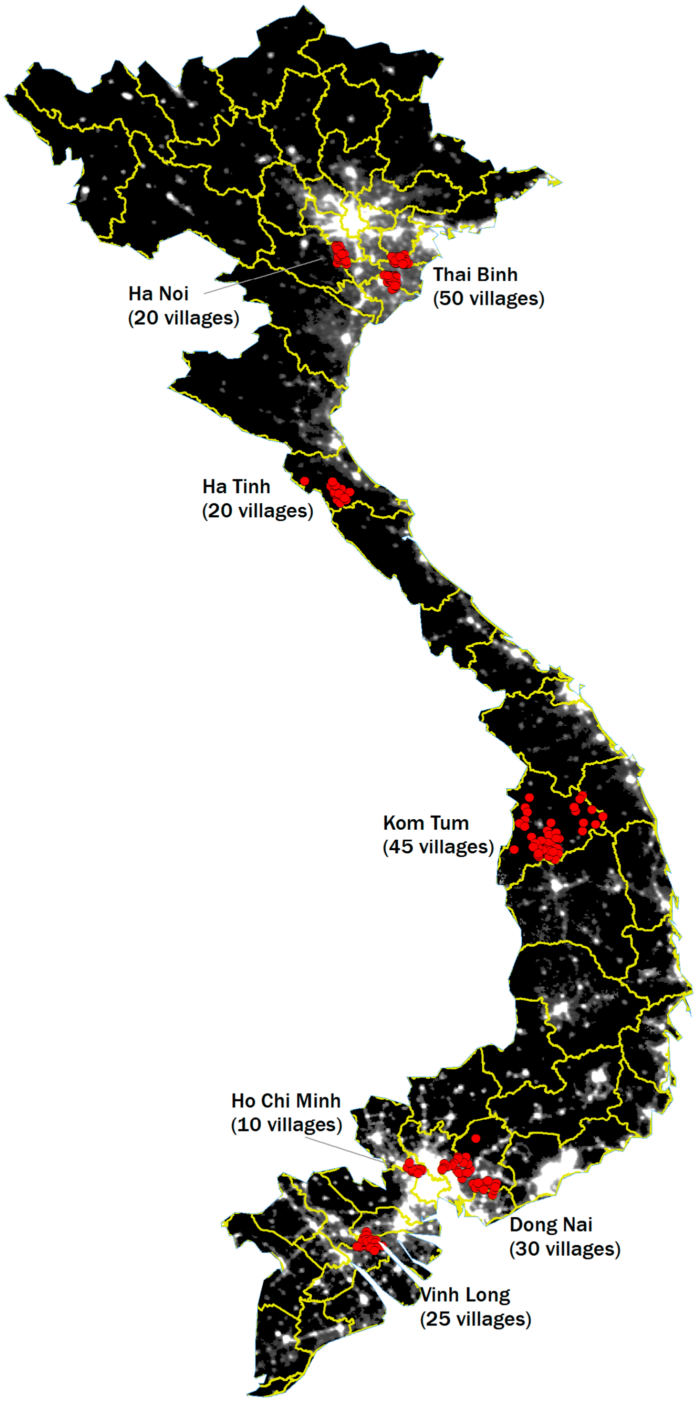
Outcome is Province Brightness	
Residential consumption	0.621 * (0.245)
Industrial consumption	−0.020 (0.100)
Commercial consumption	0.167 (0.091)
Agricultural consumption	−0.002 (0.039)
Year fixed effects	Yes
Province fixed effects	Yes
Constant	−4.776 (4.406)
Observations	382

All variables are logged
Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$

All 200 surveyed villages were electrified. Moreover, every village reported that all homes in the village had access to electricity. These trends are consistent with the fact that Vietnam has achieved near-complete electrification of all of its populated rural areas [12]. The mean village had a population of 8207 living in 2071 homes. The smallest village had a population of 1231 and 308 homes while the largest had 44,878 people living in 12,308 homes. Figure 3 shows the distribution of surveyed villages by province and their locations are plotted on the map.

In each village, the surveyor interviewed a village leader. The primary aim of the survey was to gauge the use of electricity in each village, including the number of public outdoor lights, the number of electrified public facilities (village hall, health clinics, markets and schools), frequency of power outages, and complaints regarding electricity issues. Additional inquiries were made regarding socio-economic conditions in the village (e.g., main sectors of employment, availability of services like paved main roads, piped water, mobile phone service, and internet). The survey responses show high levels of access to the grid and general satisfaction with the provision of electrical service. All of the 200 surveyed villages were connected to the main power grid and every village reported that all homes within their jurisdiction had an electrical connection. Almost all villages (91%) reported that power was available 24 hours per day. Among our 200 surveyed villages, 40 reported that the electricity was working every day over the last month, while 159 reported that electricity was working almost every day. Only one village reported that electricity was available only on some days in the last month. Village leaders are generally satisfied with the provision of electricity to their villages. When asked which public services are most in need of improvement, fewer than 10% reported electricity as the most critical concern, compared to 55% who named water. Among complaints that village leaders hear from their residents regarding electricity, 70% said that they sometimes or often heard complaints about the need for more outdoor lighting. The only other complaint heard regularly in 68% of villages was that the monthly fee is too expensive. Very few complaints were lodged regarding too frequent power cuts, poor quality service, or too high connection fees.

Figure 3. Location of surveyed villages.



The information gained from the surveys allows us to estimate the intensity of electricity usage in each village. To compare this data against satellite imagery, we acquired nightly DMSP-OLS imagery captured between 19:00 to 22:00 local time on every night from 1 August to 31 October 2013. These dates were selected to overlap and span beyond the period during which surveys were collected. In addition, we acquired monthly composite imagery for the three months of August, September, and October 2013. These composite images produced by NOAA-NGDC are processed products aimed at providing a reliable estimate of average brightness across all nightly images captured during a calendar month. Finally, we compared our survey data against light output in the 2012 annual composite of time stable night lights over Vietnam, the most recent annual image available at the time of our study.

Our main finding is that satellite sensors observe higher levels of brightness in villages with higher electricity usage as measured both by number of electrified households and by the number of public outdoor lights. We first present descriptive results showing the relationship between streetlights and luminosity and then the relationship between electrified homes and luminosity. We then present statistical analysis to derive more precise estimates of the importance of streetlights, electrified homes and other additional factors in determining brightness levels.

3.1. Streetlights

Villages with more streetlights appear consistently brighter in the daily time series, a set of three monthly composite images, and in an annual average image of time stable night lights for 2012 (see Figure 4 and Table 2).

Of the 200 villages in our survey, 121 reported no public streetlights within their villages. Most of these were in the central provinces of Thai Binh and Kom Tum, with a smaller number in Ha Tinh and Vinh Long provinces. However, it is likely that some villages reporting no streetlights may nevertheless be in proximity to public outdoor lights. For example, responses are likely to exclude large public lighting fixtures on main district roads adjacent to a village that are managed by the district government.

Figure 4. Nighttime light output and public streetlights.

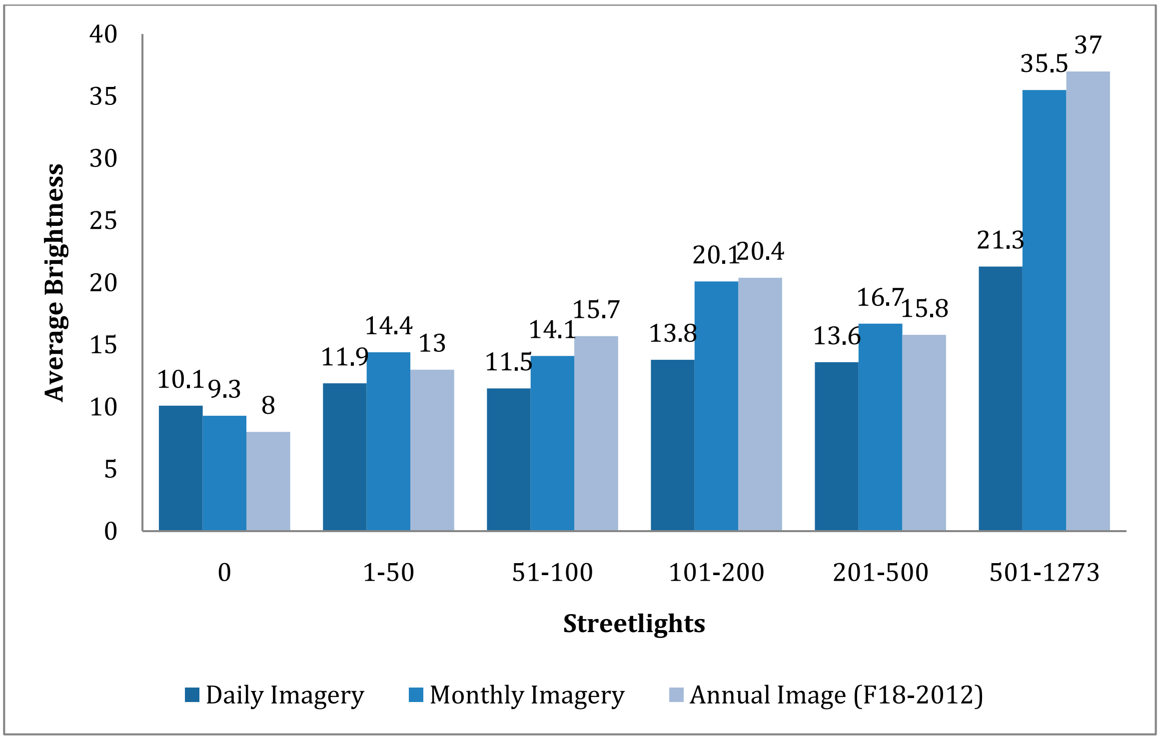


Table 2. Nighttime light output and public streetlights.

Outdoor Public Lights	No. of Villages	Nightly Brightness (Avg. of 92 Nightly Images)	Monthly Brightness (Avg. of 3 Monthly Composites)	Annual Brightness (F18-2012)
0	121	10.1	9.3	8.0
1–50	19	11.9	14.4	13.0
51–100	18	11.5	14.1	15.7
101–200	11	13.8	20.1	20.4
201–500	16	13.6	16.7	15.8
501–1273	12	21.3	35.5	37.0
Total	*200*	*11.6*	*13.1*	*12.4*

The average brightness of villages with no streetlights was 10.1 in the 90-night time series and 9.3 across the three monthly composites spanning August to October 2013. In contrast, the 12 villages with more than 500 streetlights were more than twice as bright: 21.3 in the nightly series, 35.5 in the monthly composites, and 37 in the annual composite image for 2012.

3.2. Electrified Homes

All villages in our survey reported that electricity was available in all homes in their villages. Thus, the number of homes is a reasonable indicator of how much electricity is used in a village for domestic purposes. Villages with more electrified homes appear consistently brighter in the nightly time series, the monthly composite data, and the annual composite image from 2012 (see Table 3 and Figure 5).

Figure 5. Nighttime light output and electrified homes.

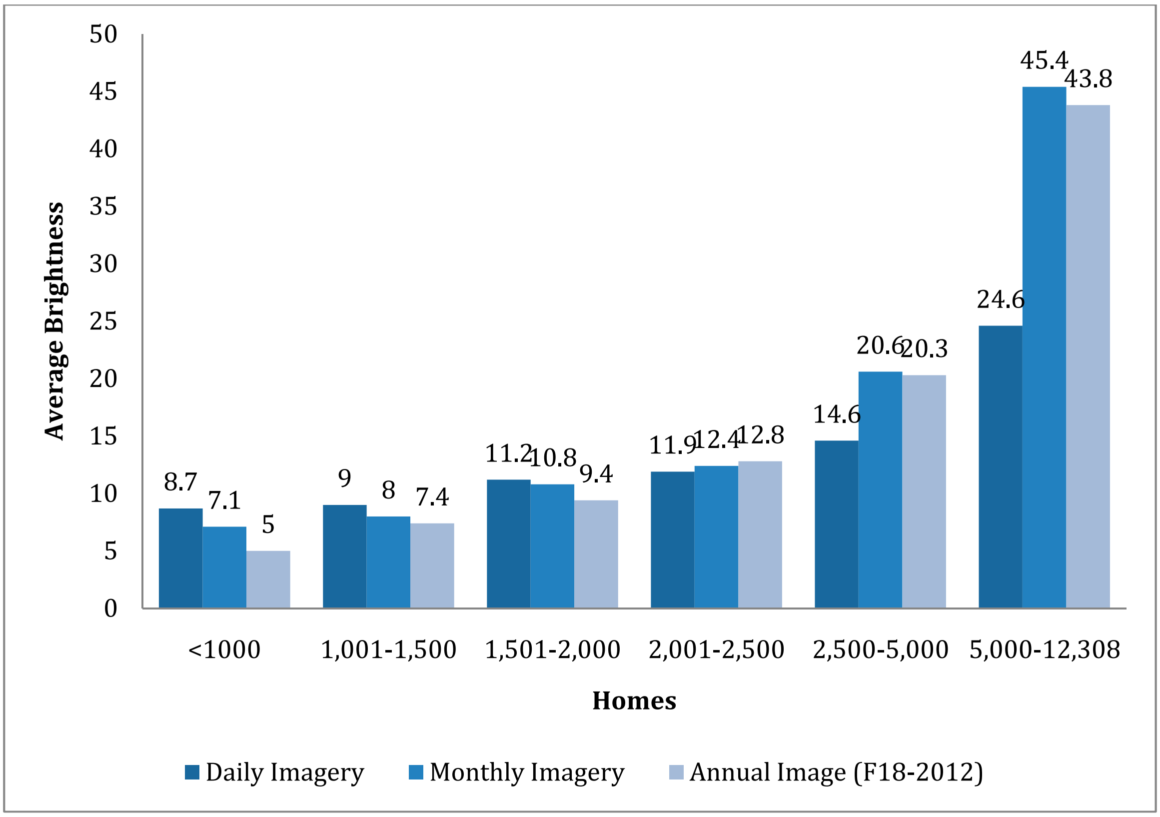


Table 3. Nighttime light output and electrified homes.

Homes	No. of Villages	Nightly Brightness (Avg. of 92 Nightly Images)	Monthly Brightness (Avg. of 3 Monthly Composites)	Annual Brightness (F18-2012)
<1000	35	8.7	7.1	5.0
1001–1500	39	9.0	8.0	7.4
1501–2000	43	11.2	10.8	9.4
2001–2500	31	11.9	12.4	12.8
2500–5000	46	14.6	20.6	20.3
5000–12,308	6	24.6	45.4	43.8
TOTAL	*200*	*11.6*	*13.1*	*12.4*

4. Statistical Analysis and Results

We conduct regression analysis to evaluate factors associated with higher light output in surveyed villages in Vietnam. The analysis shows a statistically significant and consistent relationship in which villages appear brighter when they have more public lights and more electrified households.

4.1. Nightly Data

Table 4 presents results from regressions evaluating factors that predict nighttime brightness. The unit of observation is the village-day, with 200 villages observed by satellite once each night from 1 August to 31 October 2013, resulting in a total of 18,400 observations.

The outcome variable is the brightness value observed by DMSP-OLS, which ranges from 0 to 63. Across all the models, the number of public outdoor lights and the number of homes are robustly and significantly associated with higher light output.

Models 1–5 show results from ordinary least squares (OLS) regressions with standard errors clustered on village. Model 1 shows the effect of public outdoor lights and electrified homes. We add several controls in model 2 to account for other factors that may affect the measured brightness level including proximity to the nearest town (for example, it is known that there is an atmospheric scattering effect of light around brightly lit cities in the satellite imagery), measures of cloud cover and lunar illumination as well as their interaction, and controls for latitude and longitude which may be associated with fixed geographic or climatic factors. Model 3 adds calendar day fixed effects to account for potential serial correlation in the data and to account for unusual disturbances or perturbations to measurements on specific days. Models 4 and 5 exclude outliers—observations that were more than one or two standard deviations away from the mean observed brightness in each village (typically because of elevated levels of cloud cover and lunar illumination but perhaps due to other disturbances or signal noise). The constant shows the expected mean value of the dependent variable when all explanatory variables are at zero. The R-squared values provide a statistical measure of goodness-of-fit. Robust standard errors are clustered on the village to account for non-independence of repeated observations of the same village.

The statistical effect of public outdoor lights and electrified homes is consistently positive and robust across all these models. In substantive terms, the models predict that a 1-point increase in brightness for every 125–200 public outdoor lights and an additional 1-point increase for every 550–700 electrified homes.

Table 4. Determinants of nightly DMSP-OLS light output. Data from 200 Vietnam villages observed nightly from 1 August to 31 October 2013.

	OLS				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Dependent Variable: Visible Band Brightness (0–63)				**Excl. Outliers (>2 SD)**	**Excl. Outliers (>1 SD)**
Public Streetlights (thousands)	7.9379 **	8.2307 **	8.1942 **	7.9646 **	5.2349 **
	(1.856)	(1.847)	(1.850)	(1.810)	(1.510)
Electrified Homes (thousands)	1.7250 **	1.7634 **	1.7634 **	1.7941 **	1.4070 **
	(0.253)	(0.284)	(0.284)	(0.268)	(0.243)
Distance to nearest town		−0.0440	−0.0445	−0.0363	−0.0516
		(0.048)	(0.048)	(0.048)	(0.036)
Cloud cover (infrared band values)		0.0504 **	0.0467 **	0.0380 **	0.0159 **
		(0.005)	(0.005)	(0.004)	(0.002)
Lunar illumination		10.3585 **	−8.3669 *	−9.4237 *	−2.6758
		(0.364)	(4.089)	(3.912)	(2.802)
Clouds X Lunar illumination		−0.0691 **	−0.0689 **	−0.0579 **	−0.0363 **
		(0.003)	(0.003)	(0.003)	(0.003)
Latitude and longitude controls		Yes	Yes	Yes	Yes
Calendar day fixed effects			Yes	Yes	Yes
Constant	7.7414 **	−30.4363	−29.5168	−35.4169	−26.1410
	(0.488)	(50.513)	(50.526)	(48.463)	(40.722)
Observations	18,400	18,400	18,400	17,684	13,621
R-squared	0.140	0.180	0.262	0.269	0.263
	Negative Binomial Regression				
	(6)	**(7)**	**(8)**	**(9)**	**(10)**
Dependent Variable: Visible Band Brightness (0–63)				**Excl. Outliers (>2 SD)**	**Excl. Outliers (>1 SD)**
Public Streetlights (thousands)	0.4500 **	0.4659 **	0.4702 **	0.4765 **	0.3750 **
	(0.138)	(0.132)	(0.132)	(0.134)	(0.127)
Electrified Homes (thousands)	0.1202 **	0.1151 **	0.1134 **	0.1190 **	0.1109 **
	(0.025)	(0.026)	(0.026)	(0.026)	(0.025)
Distance to nearest town		−0.0036	−0.0038	−0.0034	−0.0058
		(0.004)	(0.004)	(0.004)	(0.004)
Cloud cover (infrared band values)		0.0040 **	0.0037 **	0.0032 **	0.0015 **
		(0.000)	(0.000)	(0.000)	(0.000)
Lunar illumination		0.9627 **	−0.6425 *	−0.6587 *	−0.3650
		(0.039)	(0.313)	(0.307)	(0.293)
Clouds X Lunar illumination		−0.0061 **	−0.0061 **	−0.0055 **	−0.0036 **
		(0.000)	(0.000)	(0.000)	(0.000)
Latitude and longitude controls		Yes	Yes	Yes	Yes
Calendar date fixed effects			Yes	Yes	Yes
Constant	2.1675 **	2.2256	1.7609	1.7710	1.5471
	(0.053)	(4.690)	(4.717)	(4.814)	(4.474)
Observations	18,400	18,400	18,400	17,684	13,621

Robust standard errors clustered on village in parentheses; ** $p < 0.01$, * $p < 0.05$

While OLS regression is the most widely used statistical analysis technique, it assumes that the dependent variable is continuous and normally distributed. However, DMSP-OLS light output values are discrete count data, capped between zero and 63 with smaller values far more common than higher values. Since this distribution would violate the assumptions of OLS, we also present results using negative binomial regression, which is better suited for estimating count variables. Negative binomial regression is a method of estimating the effect of characteristics on count data and is more robust than the similar Poisson regression [19]. The results are shown in models 6–10. Overall the results are similar to the OLS regression estimates.

While the negative binomial models are more efficient than OLS, the resulting coefficients are non-linear and therefore not directly interpretable. Figure 6 plots the predicted relationship between measured brightness and the number of public lights and electrified homes using estimated parameters from Table 2, model 8. In general, the predicted brightness of a village is a positive and additive function of both the number of electrified homes and the number of outdoor public lights. As Figure 6 shows, a village with 10,000 electrified homes is predicted to be nearly three times brighter than one with 1000 homes, both for villages with no public lights and with 1000 public lights. Across most of the plotted range, the differences are statistically significant, except for larger villages with more than 7000 homes for which we have very few observations. Meanwhile, when holding the number of electrified homes constant, a village with 1000 outdoor lights is about 1.5 times brighter than one with no outdoor lights.

4.2. Monthly Data

To corroborate the results of the nightly analysis, we also compared our survey data to brightness levels observed in three monthly composite images that show average lights in August, September, and October 2013. The monthly data show patterns that are generally consistent with the results above. The average brightness of a village is strongly correlated with the number of public lights and electrified homes. The top panel of Table 5 presents OLS estimates while the bottom panel presents results from negative binomial regression. In general, the estimates show that satellites will detect a 1 point increase for every 60 additional public lights or for every additional 250–270 electrified homes.

Figure 6. Brightness increases with public outdoor lights and electrified homes. Predicted values based on Table 2, Model 8 with 95% confidence intervals.

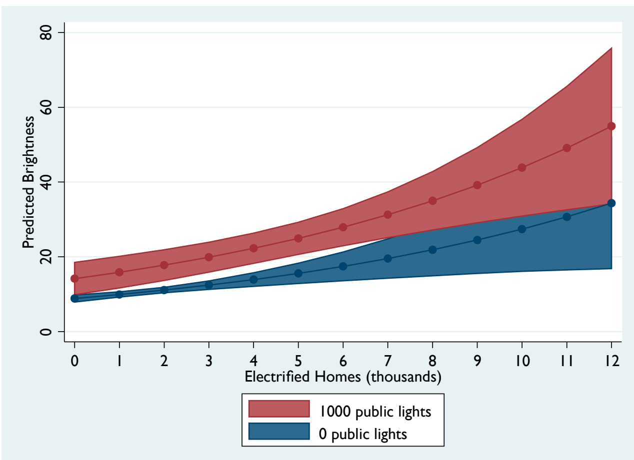


Table 5. Determinants of nightly DMSP-OLS light output. Data from 200 Vietnam villages and monthly composite images, August–October 2013.

	OLS		
Dependent Variable: Visible Band Brightness (0–63)	**(1)**	**(2)**	**(3)**
Public Streetlights (thousands)	16.1095 **	16.2860 **	16.2860 **
	(3.821)	(3.559)	(3.565)
Electrified Homes (thousands)	4.0332 **	3.7567 **	3.7567 **
	(0.486)	(0.482)	(0.483)
Distance to nearest town		−0.1352	−0.1352
		(0.076)	(0.076)
Latitude and longitude controls		Yes	Yes
Month fixed effects			Yes
Constant	3.2058 **	−69.2201	−69.0335
	(0.885)	(97.228)	(97.415)
Observations	600	600	600
R-squared	0.446	0.464	0.466
	Negative Binomial Regression		
DV: Visible Band Brightness (0–63)	**(4)**	**(5)**	**(6)**
Public Streetlights (thousands)	0.6965 **	0.6696 **	0.6670 **
	(0.250)	(0.233)	(0.233)
Homes (thousands)	0.2458 **	0.2091 **	0.2091 **
	(0.057)	(0.054)	(0.053)
Distance to nearest town		−0.0132	−0.0132
		(0.007)	(0.007)
Latitude and longitude controls		Yes	Yes
Month fixed effects			Yes
Constant	1.8872 **	5.4827	5.5682
	(0.125)	(9.694)	(9.700)
Observations	600	600	600

Robust standard errors clustered on village in parentheses; ** $p < 0.01$, * $p < 0.05$

4.3. Annual Data

As a final check, we compared our survey data to brightness levels observed in the annual time-stable average lights output produced by NOAA. This composite differs from the nightly and monthly data in that additional image processing is performed to filter out pixels with unstable light signatures. The goal is a product that reflects areas that are consistently lit throughout the world. Since there is a time lag before each annual composite is released, the F18-2012 annual composite image of time stable night lights is the most recent product available for analysis.

The results in Table 6 strongly corroborate the results from the analysis of nightly and monthly imagery, using both OLS and negative binomial regression. Brightness levels in the annual composite image increase significantly with the number of public streetlights and the number of electrified homes. Overall, the models predict a 1-point increase in brightness for every 60 public streetlights and an additional 1-point increase for every 240–270 electrified homes. These results are similar to those obtained with the monthly composite imagery, which indicates a stable electricity supply.

Table 6. Determinants of nightly DMSP-OLS light output. Data from 200 Vietnam villages and F18-2012 annual composite time stable night lights.

Dependent Variable: Visible Band Brightness (0–63)	OLS (1)	OLS (2)	Negative Binomial Regression (3)	Negative Binomial Regression (4)
Public Streetlights (thousands)	17.2642 **	17.3444 **	0.7646 *	0.6727 *
	(4.556)	(4.102)	(0.316)	(0.297)
Homes (thousands)	4.1974 **	3.7427 **	0.3221 **	0.2669 **
	(0.504)	(0.516)	(0.085)	(0.085)
Distance to nearest town		−0.1517		−0.0207
		(0.093)		(0.011)
Latitude and longitude controls		Yes		Yes
Constant	1.9654 *	−68.0609	1.8872 **	5.4827
	(0.953)	(118.537)	(0.125)	(9.694)
Observations	200	200	200	200
R-squared	0.443	0.477	–	–

Robust standard errors clustered on village in parentheses; ** $p < 0.01$, * $p < 0.05$

5. Conclusions

This study sought to evaluate the relationship between electricity usage and brightness levels observed in nighttime satellite imagery in Vietnam. Our analysis, conducted at the province-level using official administrative data and at the village-level using data drawn from an original survey, strongly corroborate the positive relationship between electricity consumption and luminosity, particularly within the residential sector. While this relationship has been observed in the industrialized world and in urban settings [6,8,20], this is among the first studies to document this pattern in rural areas in the developing world [9].

Our analysis of province level data reveals that a one percent increase in residential electricity consumption is associated with a 0.62% increase in nighttime brightness along DMSP-OLS's 63-point brightness scale. At the village level, we observed that the brightness of villages is an increasing function of both the number of electrified homes and the number of streetlights and our statistical results show that these are separate additive inputs into village brightness. A village with 10,000 electrified homes appears up to 3 times brighter in nightly satellite imagery than one with 1000 electrified homes. Meanwhile, a village with 1000 public lights is up to 1.5 times brighter than one with no public lights. These results provide the first direct evidence that even electrified rural villages with no public street lighting infrastructure can be discernible from space. A likely reason for this is the widespread use of private exterior lighting in front of homes and businesses, as well as the leakage of light from indoor electricity use. Given the safety, comfort, and convenience afforded by illumination at night, we expect it to be common that consumers use electricity to provide outdoor lighting, especially in a country like Vietnam where electricity supply is adequate and affordable.

Moreover, the lack of frequent power outages in Vietnam also makes it more likely that consumers rely regularly on electricity for outdoor illumination.

One possibility that we cannot rule out directly with our data is that villages appear lit because of the concentration of automobile headlights. Headlights are significant sources of illumination, as a typical 55-watt tungsten-halogen bulb may emit 1500 lumens of light, By comparison a 55-watt low pressure sodium streetlamp may emit 8000 lumens of lights. Thus, a large number of vehicles concentrated along a major market road would significantly increase light output, even if there was no electricity being used on that road. Yet because the satellite imagery is captured in the late evening hours and at slightly different times each night, we consider it unlikely that consistent light output signatures in a village will be driven by vehicular lighting, which will fluctuate with traffic patterns and time of day. Our analysis also did not allow us to investigate how a village's light signature is affected by the occurrence of power outages. This is because power outages, or load shedding, were not common in Vietnam during the period of our study.

Satellite-derived data will not substitute for the information that can be gathered by human monitoring of electrification projects, audits of service quality, and consumer satisfaction surveys. Yet the analysis presented here demonstrates that nighttime satellite imagery can be used to indirectly observe the use of electricity at the local level. This capability is notable because it relies on pre-existing technology and analysis of accessible data streams that are updated every night. The inferences drawn from satellite analysis may then provide guidance on how to focus limited and more costly human resources to support ongoing efforts to connect the 1.3 billion people who lack electricity around the world [10].

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Author Contributions

Min was responsible for research design, data collection, statistical analysis, and primary authorship of the manuscript. Gaba was responsible for research design, data analysis, and contributed to writing the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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