A Sustainable, UV-LED Disinfection System for N95 masks in Haiti

Brian Li

Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign, Urbana, Illinois, 61801, USA

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I. Introduction and Motivation

Third world countries may be especially hard hit by the Coronavirus (SARS-CoV-2) epidemic due to their often fragile and underfunded medical systems. Among these countries is Haiti, one of the poorest countries of the Western Hemisphere. While Haiti has reported relatively few cases, only ~100 as of the time of writing [1], thousands of Haitian workers have been laid off and are returning from the neighboring Dominican Republic, where there are over 8000 reported cases. Therefore, the number of cases may skyrocket in the near future, and Haiti's medical system is woefully underprepared to treat a widespread Coronavirus epidemic [2]. Haiti suffers from both a dearth of medical supplies and personnel, with only 25 physicians and 11 nurses per 100,000 population [3], compared to approximately 260 physicians per 100000 in the United States. In one recent instance, medical stuff refused to work at the General Hospital in the capital city of Port-au-Prince after the first cases were reported, citing a need for proper medical supplies and equipment to protect the staff themselves from contracting the virus [4].

The use of effective, sustainable disinfection methods to extend the use of existing personal protective equipment would allow the limited medical staff in Haiti to be protected from the Coronavirus and reduce their fears of being infected, while working with the constraints on medical supplies that are anticipated for the foreseeable future. In particular, N95 filtering facepiece respirators (FFR) are one of the most sought-after pieces of protective equipment to prevent exposure and contraction of the virus, which is believed to enter the body through the mouth and nose, and possibly the eyes. In this work, I propose the use of UV-LED's based on AlGaN active regions to disinfect N95 masks for re-use, as well as a Si-based photovoltaics system to sustainably power this disinfection system. I will focus on usage in a hospital or temporary medical clinic in the capital city of Port-au-Prince, the most populous city in Haiti with a population of 1 million people. However, the system should be easily applicable to other potentially affected areas.

II. Disinfection of N95 masks with UV-LEDs

Light in the so-called "deep UV" (or UV-C) spectrum have long been known to effectively disinfect both bacteria and viruses in a variety of environments, such as surfaces and equipment in medical facilities, waste water, and even air. This spectrum lies in the approximate wavelength range of 100-280nm, though the range of particular effectiveness for so-called "ultraviolet germicidal irradiation" (UVGI) lies from approximately 250-280nm. Historically, mercury-based lamps emitting at 253.7nm have been used for disinfection purposes, but rapid progress is being made in AlGaN-based LED's that can emit in this wavelength range with potentially higher efficiency, as well as a tunable range of wavelengths. The study of UVGI to disinfect N95 masks is well-reported in the literature with a wide range of doses, with at least one recent study proposing a procedure to disinfect the masks of SARS-CoV-2 specifically [5]. Encouragingly, masks have reported minimal degradation in filter capability after repeated UVGI procedures, allowing in theory for frequent reuse of the mask [6].

In the recent study for mask disinfection of SARS-CoV-2, mercury-based "UVGI towers" were used to disinfect N95 masks with 254nm radiation [5]. Doses in the two distinct ranges of 180-240 mJ/cm^2 and 900-1200 mJ/cm^2 were both found to reduce by "6 log" the number of bacterial and viral organisms, and presumed to provide a significant safety factor over the 2-5 mJ/cm^2 reported to disinfect other kinds of coronavirus on surfaces in the literature. For the purposes of this report, a 1000 mJ/cm^2 target dose was used to provide a sufficient safety factor of mask disinfection. In addition, the typical surface area of an N95 mask is approximately 190 cm^2 [7]. Therefore, the amount of energy needed to disinfect a single mask is set at 1000 mJ/cm^2 *190 cm^2 = 190,000 mJ.

III. Solar Spectrum and Irradiance in Port-au-Prince

Given the target location of Haiti, two important pieces of information are the average daily solar energy density or irradiance (MJ/m^2) and the solar spectrum in the given region. There are several designations for the total energy incident, such as direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and global horizontal irradiance (GHI). For this work, the GHI was utilized to estimate the daily solar energy available from Port-au-Prince, since it includes components of both direct and diffuse light that can contribute to generating solar power. By definition, GHI is the total amount of radiation received above the surface horizontal with respect to the ground. The Global Solar Atlas is a publicly available database owned by The World Bank Group, which provides a user-friendly map interface to provide solar irradiance values all over the globe [8]. From this database, the daily GHI in Port-au-Prince was given to be 20.77 MJ/m^2. This base value will be important in later sections for sizing the solar power system. For determining the solar spectrum in Port-au-Prince, the Solar Spectrum Calculator was used from PV Lighthouse [9]. This calculator models incident global spectrum as a function of atmospheric conditions, time of year, and latitude/longitude coordinates. The coordinates for Port Au were entered into the calculator (18.63°N, 72.45°W), and the resulting spectrum is compared to AM0 and AM1.5G in Figure 1 for the month of May. The incident power at other times of year were calculated and indicated only a ~10% variation in power (under clear sky conditions, notwithstanding variations in weather during the year). Therefore, the calculated spectra from May was used for this work.

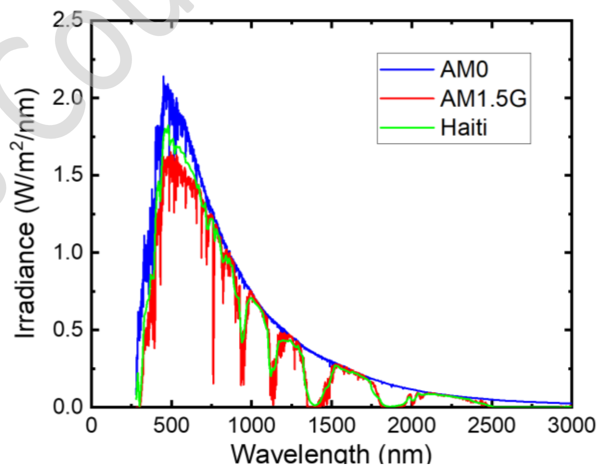

Figure 1: Comparison of standard AM0 and AM1.5G solar spectra to spectrum in Haiti in month of May. The spectrum for Haiti was acquired using the PV Lighthouse Spectrum Calculator [9].

IV. AlGaN LED and Si solar cell simulated with *Crosslight* software

The basic Crosslight structure diagrams for the simulated LED and solar cell are given in Figure 2(a). and (b)., respectively. The LED is an AlGaN LED with peak output wavelength of 267nm, within the operational range for disinfection purposes, while the solar cell is a Si p-i-n cell, which was deemed the best choice of material due to the low cost and reliability of Si cells.

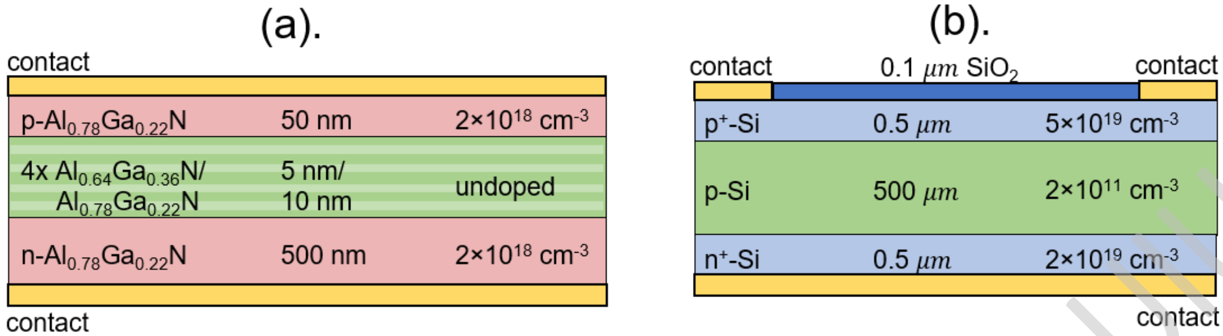

Figure 2: Schematic diagrams for (a). AlGaN LED and (b). Si solar cell, which were simulated in Crosslight.

For simplicity, the AlGaN LED used a 1D structure with top and bottom contacts rather than the more realistic lateral 2D structure with two top contacts, with an aim to achieve comparable efficiency to current AlGaN LEDs reported in the literature. The active region consists of 4× $Al_{0.64}Ga_{0.36}N/Al_{0.78}Ga_{0.22}N$ to act as the quantum well active region and barrier, based on recommended well/barrier compositions from Hirayama et. al. [10]. The thicknesses of the well and barrier are 5nm and 10nm, respectively. The outer cladding layers consisted of 2×10^{18} cm^{-3} p- and n-$Al_{0.78}Ga_{0.22}N$, with full-area contacts placed on the top and bottom. Several simplifications were made compared to results in literature. For example, reported AlGaN LEDs typically contain an electron blocking layer (EBL) with high Al composition to minimize electron leakage from the quantum wells, as well as a p-GaN top contact layer to contact the metal [11]. Attempts to incorporate the EBL did not yield improved performance while greatly increasing the time of simulation, so this layer was eliminated while the p-GaN layer is omitted and replaced with a simple ohmic contact layer directly on the p-$Al_{0.78}Ga_{0.22}N$. In addition, although the literature often cites thinner wells of ~3nm, a 5nm thickness was used here as 3nm wells had very poor internal quantum efficiency (IQE) in the simulation, possibly due to high leakage out of the wells. Radiative and Auger coefficients for the $Al_{0.64}Ga_{0.36}N$ wells were acquired from Nippert et. al. [12], which studied $Al_{0.45}Ga_{0.55}N$, yielding coefficients of $B = 2 * 10^{-11}\ cm^3 s^{-1}$ and $C = 2.3 * 10^{-30}\ cm^6 s^{-1}$, respectively. Although the composition differs from the one used in this work, these values are used due to the lack of alternative reported data for AlGaN carrier coefficients. The light extraction efficiency (LEE) was set at a fixed value of 15%. In literature, 9-10% is a typically cited value [13], so 15% would represent a reasonable high LEE compared to many existing AlGaN LEDs.

Figure 3(a) shows co-plots of the L-I curve, with units of mW/cm^2 and mA/cm^2, and the corresponding wall plug efficiency (WPE), which is the ratio of the light output power to total input power. An operational output power density of 1 mW/cm^2 was chosen in order to provide a reasonably quick disinfection time, as will be detailed in the next section, while operating close to the peak WPE. The WPE at this operational point is 4%, which is somewhat higher than typical efficiencies of 2-3% [10], and therefore represents an achievable efficiency for future deployment. Figure 3(b) shows the output spectrum with peak at 267 nm, showing the tight output distribution of the LED and suitability for disinfection.

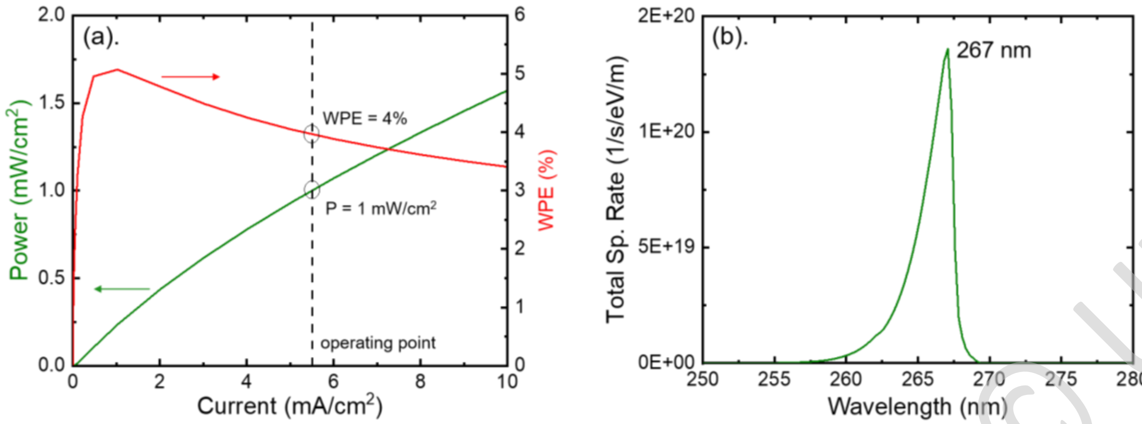

Figure 3: Performance of simulated AlGaN LED through (a). Co-plot of output power and wall-plug efficiency (WPE) as a function of input current and (b). spectral response vs. wavelength, showing peak light generation at 267 nm. The dotted line in (a). signifies an operational point with output power of 1 mW/cm^2, which is the chosen power for this disinfection system.

The solar cell used for this work was similar to the structure of the Si solar cell tutorial. The p-i-n structure consists of a 0.5 μm of n-Si doped 2×10^{19} cm^{-3}, followed by 500 μm of p-Si doped 2×10^{11} cm^{-3} (effectively undoped), and lastly a 0.5 μm of p-Si layer doped 5×10^{19} cm^{-3}, as shown in Figure 2(b). The "intrinsic" layer was greatly increased in thickness over the original 4 μm of the tutorial in order to absorb more light and improve the external quantum efficiency (EQE). Figure 4(a) compares the lighted I-V (LIV) curves using the calculated spectrum for Port-au-Prince, Haiti and the built-in AM1.5G spectrum in *Crosslight*. While the short-circuit current density (J_{sc}) for the calculated spectrum improves by 3.25 mA/cm^2 due to the higher incident flux, the actual efficiency is only ~0.2% higher as the spectrum also has an increased incident power of 1063.7 W/m^2. The maximum output power under this spectrum is 175.51 W/m^2. While the efficiency value, 16.76%, is far from the best Si module efficiencies of >20% [14], it is a reasonable value given the relatively simple cell structure, which would result in a lower cost for such a cell in real-world manufacturing. Figure 4(b) gives the external quantum efficiency (EQE) of the cell, which maintains a high ~80% value over the majority of the absorption spectrum.

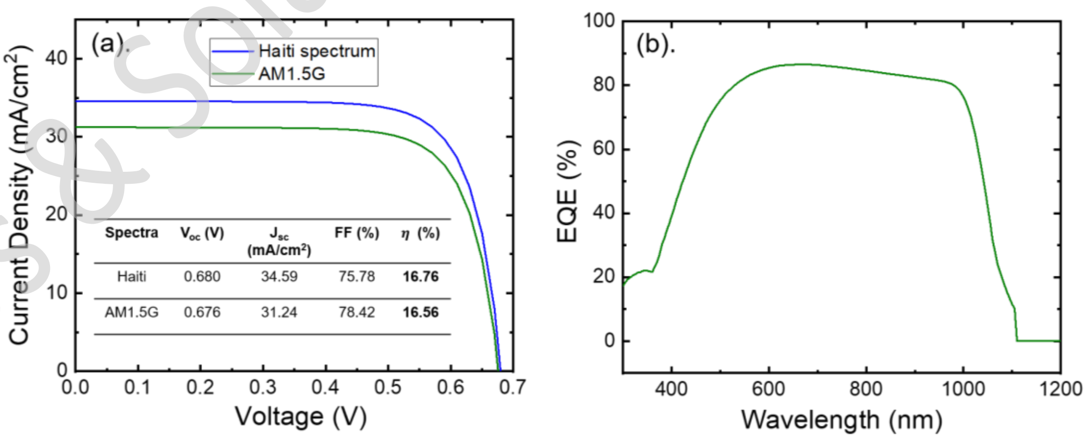

Figure 4: Performance of simulated Si solar cell through (a) LIV curves for calculated spectrum in Haiti vs. standard AM1.5G and (b) the external quantum efficiency. The figures of merit of the LIV curves are given as inset tables in (a).

V. Sizing the N95 mask disinfection system

Given the reported disinfection requirements for N95 masks and the performance of the LED and solar cell designs in *Crosslight*, the sizing of the disinfection system proceeded in the following order. First, the number of masks required per day was chosen in order to determine the total required amount of light energy from an LED array. Then, the LED wall-plug efficiency and a safety factor (in case of inclement weather, issues with power system, etc.) were accounted for to determine the amount of solar energy required, as well as battery storage requirements. The GHI of Port-au-Prince and simulated Si cell efficiency were then used to calculate the area of solar panels required to generate sufficient power for the system. Lastly, the disinfection time and physical size of the LED array are calculated based on operational power point of the LEDs and desired throughput of mask disinfection.

The determination of LED energy and solar energy requirements for the system is summarized in Table 1 and divided into "input" parameters, derived from outside sources or chosen requirements of the system, and "output" parameters, which were calculated based on both inputs and other outputs. First, the number of masks was determined by assuming 1 mask per day by 40 medical personnel, enough to serve ~100,000 in the Port-au-Prince area given the average density of medical staff currently present in Haiti. This would come out to 40 masks per day. In addition, it was decided that both sides of the mask would be disinfected, roughly doubling the energy requirement. With all of these calculations accounted for, as well as the 1000 mJ/cm^2 disinfection requirement from Section II, it was determined that 1.52×10^7 mJ of total LED energy would be required to disinfect the 40 masks on both sides. Next, the required solar energy was determined by accounting for WPE and a safety factor. As previously stated, the WPE at a power output of 1 mW/cm^2 was 4%. In addition, a safety factor of 3× the minimum required power was set to allow for several days of disinfection, primarily in the case of issues with the disinfection system or from reduced power generation due to inclement weather. With these requirements accounted for, the required solar energy was determined to be 1.14×10^9 mJ, or 1.14 MJ.

Table 1: Input and output parameters for determining the amount of LED output energy and solar energy required for the system. The final quantities are bolded and labeled by "J" and "L". Final solar energy requirement is given in megajoules (MJ) to simplify subsequent calculations.

Label	Input	Value	Justification and/or source (if applicable)
A	No. of medical personnel	40	Serve population of ~100,000 at a single location
B	Masks per worker per day	1	Assumes limited masks, and that masks can be disinfected many times without degradation
C	Sides of mask to disinfect	2	Thorough cleaning of mask
D	Safety factor	3	Enough power to run for 3 days if there is any issue with power generation
E	WPE at 1 mW/cm^2 (%)	4	Input from *Crosslight* LED simulation
F	Energy density to disinfect (mJ/cm^2)	1000	[5]
G	Surface area of mask (cm^2)	190	[7]
Label	**Output**	**Value**	**Equation**
H	Masks per day	40	A*B
I	Area of masks per day (cm^2)	15200	C*G*H
J	**LED energy per day (mJ)**	**$1.52*10^7$**	**F*I**
K	Solar energy per day (mJ)	$1.14*10^9$	(D*J)/(E/100)
L	**Solar energy per day (MJ)**	**1.14**	**$K*10^{-9}$**

The determination of solar panel area required is summarized in Table 2, and likewise divided into input and output parameters. The primary inputs were the GHI per day in Port-au-Prince of 20.77 MJ/m^2 and cell efficiency of 16.76% determined from *Crosslight*. In addition, a typical solar panel area of 1.63 meters was input to provide a physical benchmark for the system size [15]. From these inputs, it was determined that 0.33 m^2 of panel area, amounting to just 0.20 typical solar panels, was sufficient to power the given system. In terms of battery storage, the battery should be able to provide at least 1.14 MJ (or 0.317 kWh) of energy, an energy requirement easily met by even a single storage battery, as typical solar batteries having greater than 1 kWh of capacity [16].

Table 2: Input and output parameters to determine the area of solar cells needed to power the system. The final values for area and number of panels are given by labels "EE" and "FF". The calculation for EE utilizes the quantity L from Table 1.

Label	**Input**	**Value**	**Justification and/or source (if applicable)**
AA	GHI per day in Port-au-Prince (MJ/m^2)	20.77	[8]
BB	Cell efficiency (%)	16.76	Input from *Crosslight* Si cell simulation
CC	Average solar panel area (m^2)	1.63	[15]
Label	**Output**	**Value**	**Equation**
DD	Generated energy density per day (MJ/m^2)	3.48	AA*(BB/100)
EE	**Area of cells needed (m^2)**	**0.33**	**L/DD**
FF	**No. of panels needed**	**0.20**	**EE/CC**

Lastly, the disinfection time and LED array size were calculated, and the inputs and outputs are summarized in Table 3. The array is assumed to be in a planar, single-sided configuration, rather than an enclosure design. The first main input is the LED power, which is set at 1 mW/cm^2 as defined previously. Next, a "packing density" of LEDs on an array, defined as the percentage of the array area that has LED emission, was set at 25%. This value is important because it reduces the "true" power density of the array and increases the disinfection time. Lastly, the number of masks disinfected in a single batch was set at 10, which is the primary determinant of the required array size. In the outputs, the "array LED power" was calculated to be 0.25 mW/cm^2 when accounting for the individual LED power and packing density. Next, the disinfection time for a single side of the masks was calculated by dividing 1000 mJ/cm^2 by the 0.25 mW/cm^2 array power, which resulted in a disinfection time of 66.67 minutes. If the masks are simply flipped to disinfect the other side, the total time is doubled to 133.33 minutes for the disinfection of a batch of 10 masks. Since only 40 masks are required per day, this disinfection time should be more than sufficient for the required throughput, with a total of ~9 hours required operational time. Lastly, the minimum array size is determined simply by multiplying the mask area by 10, for an array size of 0.19 meters. This size is portable and could be easily installed in a hospital location.

Table 3: Input and output parameters to determine the disinfection time and LED array area. These two quantities are labeled as "FFF" and "GGG". In addition, it is noted that EEE, FFF, and GGG are calculated with quantities defined in Table 1.

Label	Input	Value	Justification and/or source (if applicable)
AAA	Individual LED power (mW/cm^2)	1	Chosen from *Crosslight* simulation, close to peak WPE while allowing short disinfection time
BBB	Packing density of LEDs in array (%)	25	Approximation from studying LED array configurations; number may vary widely
CCC	No. of masks in a "batch"	10	Trade-off between sufficient throughput and limiting LED array size (to ensure compactness + low cost)
Label	**Output**	**Value**	**Equation**
DDD	Array LED power (mW/cm^2)	0.25	AAA*(BBB/100)
EEE	Disinfection time per side (min)	66.67	F/BBB/60
FFF	**Disinfection time per batch (min)**	**133.33**	**EEE*C**
GGG	**LED array area (m^2)**	**0.19**	**CCC*G*10^{-4}**

VI. Conclusion

In this report, a UV disinfection system based on AlGaN LEDs and Si solar cells was proposed to disinfect N95 masks in Port-au-Prince, Haiti. It was found that for a requirement of 40 masks per day to supply 40 medical personnel, serving a population of ~100,000 people, a single Si solar panel and battery were in fact greatly over-sized to fulfill the power needs for mask disinfection. In addition, a 0.19 m^2 LED array was sufficient to disinfect all 40 masks on both sides in a combined span of ~9 hours, well within the daily requirements. The over-sizing of the system was an unexpected if welcome result, and suggests that the availability of medical personnel and medical supplies could be a greater bottleneck to usage rather than disinfection capabilities.

There are multiple ways in which the excess power could be utilized. For example, if personnel are supplied with multiple masks instead, which is preferable, the system has the capacity to disinfect more masks than originally designed, and in any case could be easily scaled. The system could also be utilized towards disinfecting other medical equipment. One last application could be to perform mask disinfection at a “central location” from which other hospitals could pick up disinfected masks, thus maximizing use of the solar power to simply disinfect as many masks as possible over the course of the day.

VII. References

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