GLOBAL ENERGY ACCESS NETWORK CASE STUDIES

SUSTAINABLE ENERGY & TECHNOLOGY

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Foreword

Heidi Vreeland

Heidi Vreeland (heidi.vreeland@duke.edu) is an Environmental Engineering doctoral candidate at Duke University's Pratt School of Engineering.

Improving access to affordable, reliable, and sustainable energy is pivotal in addressing the multifaceted needs of global development, as energy access has important implications for socioeconomic benefits, human health, and the environment. However, one billion people still lack access to electricity and over two billion people still use polluting biomass fuels for cooking and heating (World Bank, 2018). The challenges surrounding energy poverty are complex and will certainly require multidisciplinary approaches. The Global Energy Access Network (GLEAN) provides Duke University students with opportunities to share relevant experiences and discuss diverse perspectives on energy access issues by uniting graduate, undergraduate and professional students across disciplines.

One way GLEAN members have been able to disseminate knowledge from their experiences is by authoring case studies that reflect on important takeaways and lessons learned from their work and research.[1] The idea to compile these case studies was conceived during our inaugural year (2016-17), when we noticed that many students had gleaned qualitative insights from encountering energy access issues in their fieldwork—even those not directly working on energy access projects. By composing a distinct compilation of case studies that highlights quantitative results and also delves into qualitative takeaways, we hope that this new volume is shared broadly so that others can benefit from our collective experiences.

[1] The first volume of student-authored case studies is openly available online: http://hdl.handle.net/10161/15400

This second volume of GLEAN case studies highlights two key points of opportunity for addressing current energy access challenges: modern energy technologies and effective energy policy. The case study by Valerino discusses how the energy yield of photovoltaic cells can be compromised by poor air quality and what this could mean for countries like

India that have intentions to increase reliance on solar energy but also suffer from high levels of air pollution. Kumar reflects on how lessons from India can help other developing nations finance renewable energy projects in innovative ways. Klug's case study examines how reliance on traditional biomass fuel has affected a community in Madagascar, and Hunter presents the importance of propagating suitable technologies that are robust and cater to the unique social and cultural needs of diverse communities by highlighting his own experiences on implementing biogas-fueled sanitation systems in the Philippines. Most authors shared that the process of deeply reflecting on their experiences and iterating on manuscripts with reviewers from multiple disciplines has helped them understand their work more clearly and taught them how to better communicate to a wider, multidisciplinary audience. We feel that the work presented here is exciting and relevant to those interested in energy access research, and we hope that readers enjoy learning more about these unique case studies and find the content to be stimulating and insightful.

GLEAN is housed within the Duke University Energy Initiative.[2] It was generously supported between 2016 and 2018 by a Duke Support for Interdisciplinary Graduate Networks (D-SIGN) grant.

[2] http://energy.duke.edu/

Development of an Inexpensive Solar Soiling System to Analyze Global Influence of Dust and Particulate Matter on Photovoltaic Efficiency

Michael Valerino

Michael Valerino (michael.valerino@duke.edu) is an Environmental Engineering doctoral candidate at Duke University's Pratt School of Engineering.

Keywords: soiling, aerosol deposition, dust accumulation, PV performance

In 2016, 75 Gigawatts of solar photovoltaic (PV) power was added around the globe, equating to 31,000 solar panels installed every hour (REN21, 2017). PV energy production can be negatively impacted (>30% power production loss) by the deposition of ambient atmospheric dust and particulate matter (PM) (Bergin et al., 2017; Javed et al., 2017; Sayyah et al., 2014). Particle deposition on PV panels is known as soiling. Regions of the world that regularly experience high concentrations of PM (e.g., Eastern China), frequent dust events (e.g., Arabian deserts), or both are most at risk for significant losses in energy yields due to soiling.

In developing countries, solar power was the biggest renewable energy investment at $57.5 billion (USD) in 2016 (REN21, 2017). Of new PV installations, a growing fraction is rooftop solar. India, for example, has a projected goal of 40 Megawatts of rooftop solar alone by 2022. However India is also highly susceptible to soiling due to elevated levels of air pollution. As the use of solar energy increases globally, there is a need for better and more affordable commercial soiling monitors as well as a solution for monitoring performance of private, rooftop solar grids.

Current soiling monitoring technology is expensive (>$5,000 USD) and may not be representative of soiling impacts (El-Shobokshy and Hussein, 1993; Figgis et al., 2016; Geuder and Quaschning, 2006; Schill et al., 2015). There are currently no low-cost (<$500 USD) options for monitoring PV soiling. Due to this lack of low-cost devices, research utilizing more than 1 monitor is extremely limited. In fact, the majority of studies only measure soiling at a single monitoring site and only use 1 (expensive) monitor to do so (Costa et al., 2016; Maghami et al., 2016; Sayyah et al., 2014). This creates a gap in understanding as the rates, sources, and environmental conditions that impact soiling differ globally (Bergin et al., 2017). Thus, having access to an array of inexpensive monitoring devices, which could be deployed across multiple locations, would be a valuable research asset. Even within a single site, soiling has been observed to be highly variable; hence, multiple monitoring locations have significant potential with commercial industries that utilize solar farms for energy (Gostein et al., 2013). A low-cost monitoring system would help better characterize global soiling, and address the need for reasonably priced soiling monitors.

To improve understanding of global soiling and meet the needs for affordable PV soiling monitors, the goals of this project are:

1. Develop an inexpensive system to monitor PV soiling
2. Deploy system across 3 heavily impacted global regions to evaluate system performance, PV cell temperature effects, meteorological impacts, and to analyze composition of particles deposited on PVs
3. Generate a global model to predict soiling rates over resolved temporal and spatial scales

Goal 1: Prototype Development

Researchers at Duke University are in the process of developing an inexpensive (∼$250) and portable monitoring system. The prototype (Figure 1) utilizes two 5-Watt polycrystalline solar panels (Eco-Worthy brand). In order to observe how particle deposition onto the PV surface (i.e., soiling) compromises solar panel performance, 1 of the 2 side-by-side panels is regularly cleaned for comparison with the panel on which particle deposition continuously occurs. Power generation and system parameters are documented using a printed circuit board (PCB). The system also monitors back-of-module temperature (BOM-T) of the solar panels, which is an important (though indirect) indicator of PV efficiency, given that elevated temperatures correspond to a decrease in solar cell efficiency. BOM-T has been shown to increase or decrease due to soiling, depending on factors like soiling rate (i.e., the percent of soiling per day) and uniformity of particle deposition.

I have demonstrated the capabilities of the prototype system by comparing it to a Campbell Scientific SMP100 Soiling Station (∼$9,000

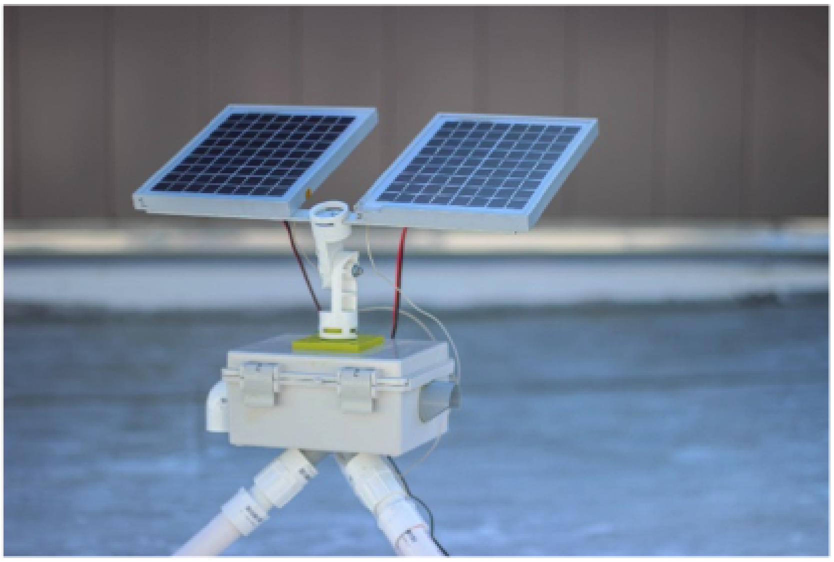

Figure 1: Low-cost prototype being tested on rooftop at Duke University

USD), which is representative of standard commercial soiling monitors. As with the prototype, the Campbell Station is comprised of 2 side-by-side PV panels. Both sets of solar panels (Campbell Station and prototype) were oriented due south at a 25-degree tilt and preliminary tests were performed on the roof of the engineering building at Duke University over a 3-week duration of the 2017 fall semester. The purpose of this initial test was to ensure that the designed prototype was working as expected (i.e., continuously monitoring and recording time and energy data for both sets of PV panels). As expected, we did not observe impacts from soiling since air pollution is well controlled in this region. The R^2 correlation between the dual panels of the prototype, and dual panels of the Campbell Soiling Station were 0.999 and 0.987, respectively. A cross-comparison of the corresponding panels on the prototype and Campbell Station was observed to have an R^2 correlation of 0.85. Results demonstrate that all panels were able to reliably record fluctuations of incoming solar radiation. These changes in incoming radiation are clearly exhibited in Figure 2, which demonstrates the variation of a cloudy day; results demonstrated reliable performance. On sunny days, the prototype's performance (compared to Campbell Station) is even better, as the panels have consistent power output.

After completing initial performance tests, a prototype was sent to Gandhinagar, India where it is currently being field tested, and preliminary data show promising results. Over a 2-week period, the prototype documented how solar panels lost efficiency as soiling increased. By the end of the test, soiling had decreased PV efficiency by nearly 20% (Figure 3), which matches the soiling rates expected in this region. The

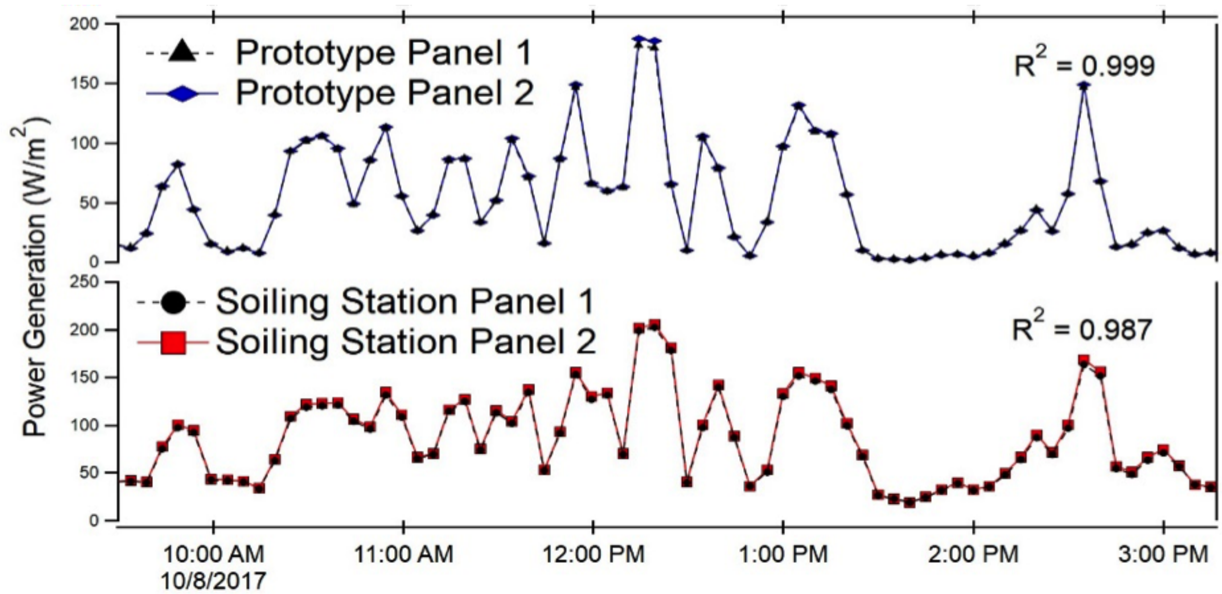

Figure 2: Comparison of the prototype with the Campbell Station on a cloudy day October 8, 2017. Data points are 5-minute averages of power generation by the solar panels. All panels were cleaned prior to deployment.

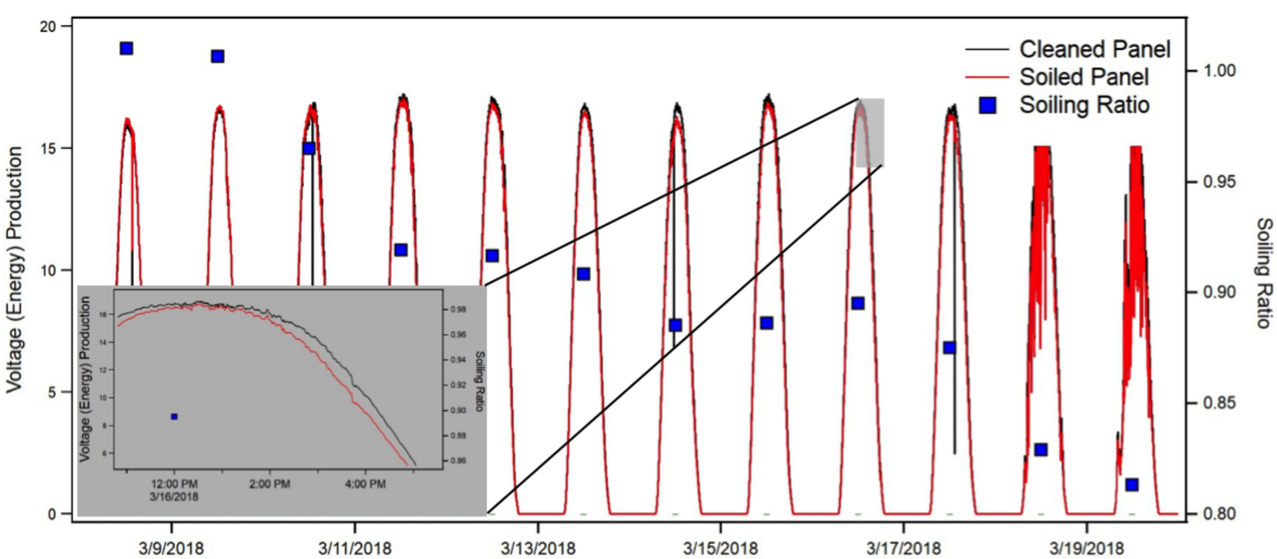

Figure 3: Prototype monitoring data from March 8-20, 2018 in Gandhinagar India. 20% soiling occurred over the monitoring period. The inlet graph shows an example of the difference in power generation between cleaned (black line) and soiled (red line) panels.

soiling ratio (blue square markers in Figure 3) is defined as the ratio of soiled/clean performance (where a soiling ratio of 1.00 means that both panels have the same performance and are producing the same amount of energy). By the end of the monitoring period, the soiling ratio was $\sim$0.80, meaning that the soiled panel produced only 80% of the energy that the cleaned panel was producing.

Goal 2: Field Deployments

In summer 2018, I plan to continue field testing in India with a full-scale pilot project where 5 low-cost prototypes will be deployed on the campus of ITT-Gandhinagar over a 4-month duration. Pilot study measurements will include:

1. Continuous recording of solar panel power output and cell temperature (BOM-T) by the prototype, and comparison of the prototype with the Campbell Scientific Station, and the output of on-grid panels.

2. Every 21 days, deposited particulate matter will be collected from the uncleaned solar panel, so that composition and particle properties can be analyzed

3. $\mathrm{PM}_{2.5}$ will be measured continuously alongside the soiling measurements using a light scattering sensor system developed in Dr. Mike Bergin's lab at Duke University.

4. 24-hour filter measurements will be used to determine ambient PM speciation.

After completing this pilot study, a network of 10 prototype systems will be deployed in sunbelt regions, which include systems in India, East China, and the Arabian Peninsula and are known to be heavily impacted by soiling (Hauff et al., 2011). Soiling rates, ratios, contributing sources of dust and PM, and important meteorological processes will be analyzed over the three regions. This work will address the existing gap in knowledge characterizing PV soiling conditions across global regions.

Goal 3: Global Model

In order to fulfill the critical need of mitigating negative impacts from dust and PM on PV efficiency, a model for MAPSOLE (Minimizing Air Pollution Impact on Solar Energy Production) will be developed. The MAPSOLE model will first compare the loss in solar transmittance from the prototypes (as measured by power production of soiled vs. cleaned panels) to the predictive model outlined in Bergin et al. (2017).

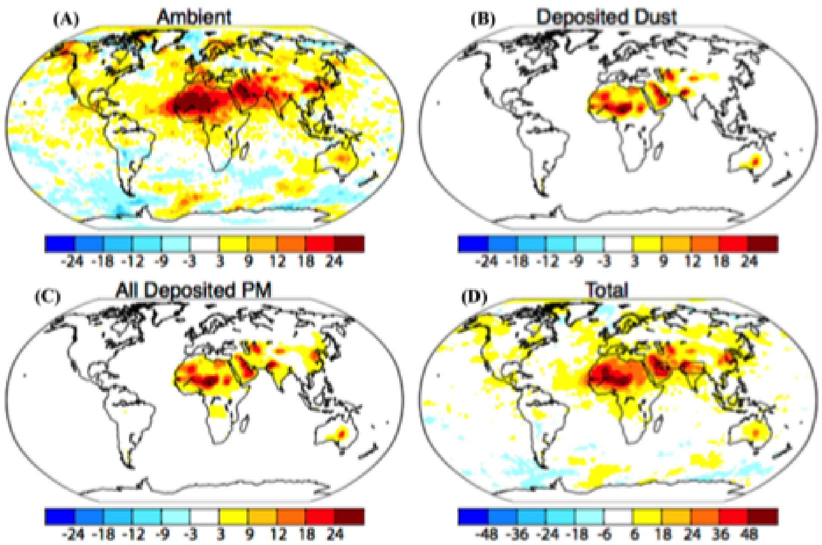

Figure 4: Predicted transmittance loss due to: (A) ambient PM; (B) deposited dust; (C) deposited dust and PM; (D) total impacts of aerosols. These results are derived from Equation (1) as input into a NASA GISS Model (Bergin et al., 2017). The scale is percent loss in solar power generation.

$$\frac{\Delta T}{PM_F} = -\frac{1}{PM_F} \sum_{i=1}^{n} \left(E_{abs,i} + \beta_i E_{scat,i}\right) PM_{F,i} \qquad (1)$$

where ΔT is change in transmittance, PM_F is mass loading on the $(g \cdot m^{-2})$, E_{abs} is PM absorption efficiency, E_{scat} is PM scatter efficiency, and β is the PM upscatter fraction. The four components analyzed are dust, organic carbon, elemental/black carbon, and light scattering ions (which are important because they interact with light and have the potential to negatively impact PV performance).

Equation (1) can then be input into a version of the NASA GISS ModelE2 with collaboration from Professor Drew Shindell at Duke University. This version is nearly identical to the Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCIMP) (Schmidt et al., 2014; Shindell, 2014), which uses 40 atmospheric layers, and a 2° by 2.5° (latitude by longitude) resolution. This model calculates deposition fluxes of dust and aerosol species, as well and shortwave radiation reaching the ground. Emissions (natural and anthropogenic) and deposition rates of both dust and other PM are calculated in the model.

Results of this model are combined with the losses determined by Equation (1), culminating in the MAPSOLE model. Preliminary results of this model are shown in Figure 4. This model will allow for highly-resolved estimations of soiling impacts from deposited dust and PM. This information will provide important insights for the renewable energy sector. Cleaning costs and energy losses due to soiling equate to \$116 million USD per year for Saudi Arabia alone (Baras et al., 2016).

Cleaning schedule considerations are crucial for profit-optimization. Finding the optimum point between cleaning costs, and energy loss due to soiling, is necessary for profitable operation (Abu-Naser, 2017; Dolan et al., 2015; Jones et al., 2016). Since the optimal time to clean PV panels varies regionally and seasonally, MAPSOLE will allow PV energy producers to make informed decisions about when to clean solar grids.

Conclusion

As photovoltaics are being installed and used as renewable energy sources at an exponential rate, the negative impacts from PV soiling have become increasingly relevant. For instance, China and India, which are notorious for poor air quality, account for over 50% of global PV use. Interest in PV energy is also growing in the Middle East, with Dubai adding a 200-Megawatt plant in 2017 (REN21, 2017).

A significant fraction of new installations is rooftop solar. Expensive monitoring solutions are not feasible for owners of rooftop grids, creating a need for a low-cost monitoring system. Since the prototype in development can measure soiling impacts at a fraction of current costs, it will be both a valuable research tool, and an affordable solution for monitoring private solar grids. Further, future commercial utilization of the system has high potential for user benefits, such as allowing users to be alerted of the current state of their rooftop grid. This will allow users to make informed decisions on cleaning procedures, which can be costly and labor intensive, especially in regions without year-round access to clean water. This system offers potential benefits for commercial PV owners as well as private/individual users in both urban and rural regions.

It is estimated that by 2030, PV systems will reduce carbon emissions by 69 to 100 million tons annually (Hosenuzzaman et al., 2015). Climate change has already impacted human and environmental health, and the need to move towards a sustainable future has never been greater. PV systems that operate at maximum efficiency are crucial in achieving this goal. With observed soiling losses exceeding 30% in a matter of weeks, a greater understanding of soiling, as well as low-cost monitoring solutions, represent a global requirement that this project will help to fulfill.

Exploring Cost-Effective Debt Financing for Renewable Energy Companies in Developing Nations: Insights from the Indian Experience

CHINMOY KUMAR

Chinmoy Kumar (chinmoy.kumar@duke.edu) is a Master of International Development Policy candidate at Duke University's Sanford School of Public Policy.

THE AVAILABILITY OF CHEAP RENEWABLE ENERGY (RE) for developing nations has become key to sustainable global development. As majority of the world's population live in developing nations, it is crucial that these nations embrace various clean energy sources for meeting their own increasing energy requirements. The Paris Agreement on climate change has urged global nations to gradually reduce greenhouse gas emissions and to increase reliance on RE. Though many developing nations have been recognized as emerging leaders in sustainable energy with robust policies (World Bank, 2017), the challenge for them is to facilitate cost-effective finance for the entities engaged in this sector considering the huge capital outlay and long-term financing nature of RE projects (Nelson and Shrimali, 2014).

Given the low level of savings and scarce public investment resources in many developing nations, cost-effective financing for such projects remains a concern. Several innovative ways are being adopted by RE firms to obtain low-cost finance for their projects. One such popular route being adopted is foreign currency borrowings from overseas investors. This source of funding appears attractive considering the interest rate differential between the developed and developing nations. However, such borrowing is fraught with risks that could potentially jeopardize a firm's entire project. In addition, excessive foreign currency debt may not be desirable for many nations; indeed, several nations have clamped down on excessive foreign currency debt due to macro-economic stability concerns. In view of the above, developing nations need to put in place prudent policies which enable the domestic firms to mobilize resources in a cost-effective manner without compromising macro-economic stability.

In this case study, I present insights from the experience of India, which has embraced RE sources for both reducing the level of emissions and meeting its growing energy demands. Incidentally, India is the world's third largest carbon emitter and in 2015 had set up an ambitious goal of increasing its renewable power capacity to 175 Gigawatts (GW), including 100 GW from solar, 60 GW from wind, 10 GW from biomass and 5 GW from small hydro projects (Ministry of New and Renewable Energy, 2016). In the Paris Agreement, India further affirmed its commitment to fight climate change. It has pledged to reduce its energy emission intensity up to 30–35% by 2030 from the 2005 levels and also increase the share of non-fossil fuel energy to 40% of India's energy mix by 2030 thereby reducing carbon emissions (Jaiswal, 2017). While several initiatives have been taken by the government, policy-makers, and other key stakeholders to provide a conducive environment to facilitate generation of RE in the country, the availability of adequate and cost-effective finance remains elusive and shall be the key to successful transition from fossil fuels to sustainable energy sources for India.

Financing challenges: Domestic constraints

The Indian firms engaged in RE are faced with high capital expenditure and difficulties in raising long-term finance (mainly debt) in a cost-effective manner. Most of these firms are small and also new to this non-conventional energy generation space. Therefore, equity investment into many of these firms may not be forthcoming and debt financing would be an important source of funding for many of them. In order to achieve RE goals and enable clean energy to compete with fossil fuels, it is imperative that such finance opportunities are cost-effective. Although investment in RE and energy efficiency is picking up both globally and in India, the scale of investment does not yet match the scale of financing needed for the sector to grow rapidly. It has been estimated that $200 billion (USD) of investment will be needed in the renewable energy sector in India by 2021/22 (Buckley and Sharda, 2015).

This scale of funding can be demanding for the Indian economy at present for several reasons. The Indian banking industry is currently hesitant to offer such financing due to rising non-performing loans in infrastructure projects relating to energy sector. Also, the lack of adequate understanding of this new sector is constraining banks from increasing their exposure into this area. Recently, a few Indian banks have started sanctioning loans to a small number of projects, but this is inconsequential considering the much larger scale of investment needed for entire sector. Non-banking financial institutions are also unable to significantly contribute due to their own lack of appraisal and financial capacity. The domestic corporate bond market is another avenue where companies can mobilize resources. However, in India, the corporate bond market is limited. Only a few blue-chip corporations are able to raise finances at a competitive rate, but for other smaller and relatively newer firms this may market may not be suitable (India Index Services & Products Limited, 2017). Companies with lower ratings are unable to raise funds by selling bonds in the domestic market due to the preference of local investors for high-grade bonds. In view of above reasons, the domestic sources of funding may not be attractive for many of these new Indian renewable energy companies.

Concerns with external debt

Foreign investors can play an important role in bridging this gap of demand and supply for funds. Further, RE firms may find these sources of financing attractive in terms of lower interest rate, longer tenor, etc. However, foreign sources of funding come with concomitant risks for Indian companies. Due to their small size, many of these firms most likely will not have robust risk management systems in place. Therefore, while such foreign currency borrowings from overseas investors may look attractive (given the low interest rate regime prevalent in most advanced economies, overseas investors would search for higher yield in the emerging economies), such borrowings expose Indian firms to foreign exchange volatility risk. Since there will be a mismatch between debt payments (which would be in a foreign currency) and revenues earned (in the local currency), the companies that avail foreign currency loans shall have to repay their foreign currency debt obligations from the revenue generated in the local currency. For example, if a company borrows in US dollars, and if the US dollar appreciates, the company shall be exposed to foreign exchange risk as its revenues will be in Indian Rupees and not in US dollars. The extent of the risk/loss nevertheless shall depend upon both the quantum of foreign currency loans availed and volatility the currency pairs. So in absence of robust risk management system, in terms of treasury operations, experienced traders/dealers, risk managers etc., such foreign currency debt can turn out to be potentially detrimental if there is an adverse currency movement.

Most of the firms which borrow in foreign currency usually manage their foreign currency risk by hedging it. But hedging involves a cost and it can then negate any advantage arising from the cheaper foreign currency loans. For firms with expertise in risk management or firms which have a natural hedge, foreign currency debt may be a good business decision. For instance, there are certain firms (export oriented) with foreign currency debt have revenues in foreign currency and therefore are immune to foreign exchange risk. As many Indian RE firms are relatively small and do not have the experience or expertise to effectively address these issues, exposures to such borrowings can be catastrophic if these exposures are unhedged (Bolshaw, 2013). On the other hand, if they are hedged using the foreign exchange derivative instruments, the cost of the borrowings shall no longer remain low due to the cost of hedging. In most countries, the typical hedging instruments include foreign exchange forwards and options. Firms, in order to use such derivative instruments to cover foreign exchange risks, need to buy them from sellers (usually commercial and investment banks). When one adds the cost of these derivative products with foreign currency interest rates, the overall cost of borrowings go up. If we take a hypothetical case of an Indian firm borrowing in US dollars from an overseas lender at approximately 7% (US interest rates plus the credit risk premium) and then buying a hedging instrument for about 6–7%, the cost of borrowing effectively becomes 13–14% which may work out to be the same if the firm had borrowed in the local currency domestically.

Also, the rising foreign currency debt obligations may not augur well from the macro-economic perspective of a developing nation. Recall that the East Asian financial crisis of late 1990s was a fallout of excessive foreign currency debt by corporates in some of the Asian nations. To contain unbridled foreign currency borrowings by Indian corporates, there are policy provisions applicable to the Indian firms in terms of the tenor of loans, end-use of funds received, and on the maximum interest rate of such foreign currency loans. These restrictions are in place as the Indian Rupee is not fully convertible on capital account and there are certain restrictions on free movement of capital in and out of the country. In 2014, there was a case of an Indian Renewable Energy company, which had indulged in such a foreign currency borrowing that violated the regulations (Stanton, 2014). The company, as per new reports, had flouted the External Commercial Borrowings (ECB) regulations by borrowing at a higher rate than the prescribed rate of interest. Such borrowing endangered the entire project for the company as it was violation of law of the land.

Specific case of an Indian RE firm: Greenko Group

Greenko Group, an Indian-based Independent Power Producer (IPP) with a diversified portfolio of about 700 MW in operational RE assets and another 300 MW in additional RE projects, is one of India's leading clean energy companies. In July 2014, it raised $550 million (USD) from overseas investors by offering unsecured bonds at a yield of 8%. The overseas issuer, Greenko Dutch BV (one of its subsidiaries), sold

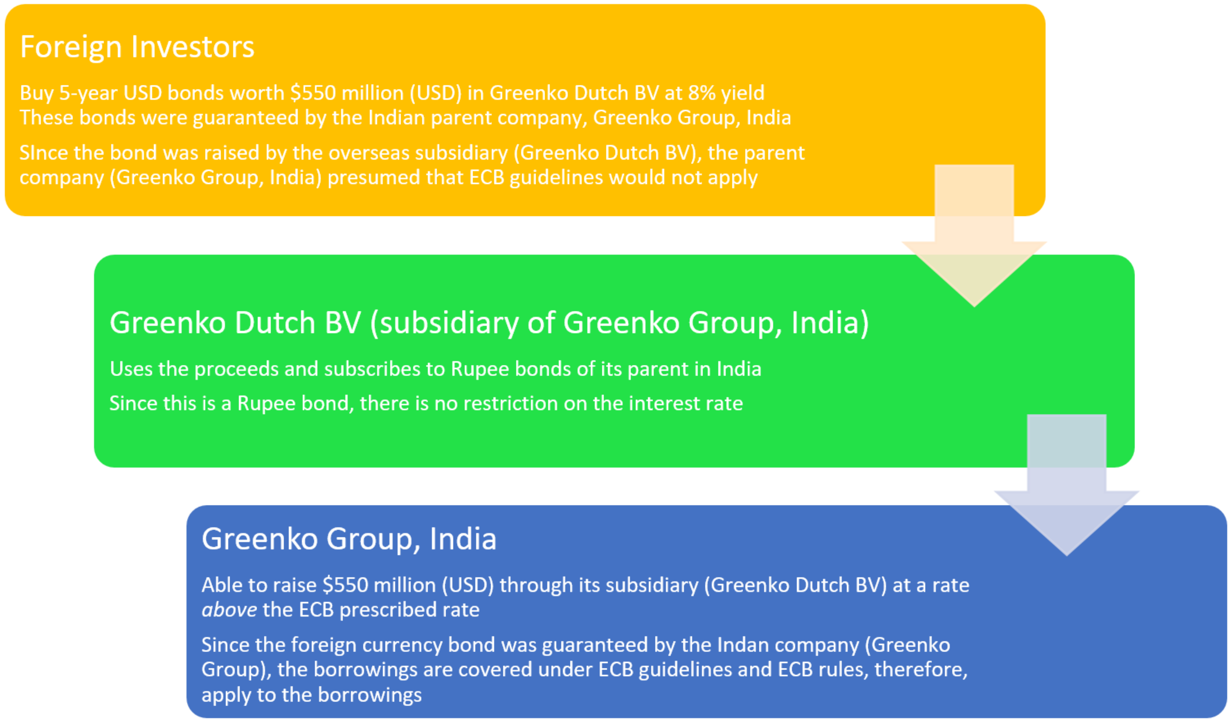

Figure 5: Structure of borrowing

USD bonds guaranteed by Greenko Group and the proceeds were used to subscribe to Indian Rupee bonds from a group of entities in India holding various power assets (Figure 5). The structure was intended to give the offshore vehicle recourse to onshore assets. The deal took advantage of a change to the regulation which allowed issuers to sell Indian Rupee denominated non-convertible debentures to offshore entities without being subject to the Libor + 500 basis points (bps) funding cap. While the company was eligible to borrow from the overseas investors, it violated the extant External Commercial Borrowings (ECB) policy norms regarding the maximum interest rate offering. The Indian company used this structure to route transaction through its overseas subsidiary to essentially circumvent the prevalent ECB guidelines. The subsidiary raised money in the overseas market at a rate higher than the Libor + 500 bps and used the funds to buy the bonds issued by the parent in Indian Rupee. The ECB guideline does not allow Indian companies to borrow at a rate higher than Libor + 500 bps but in this case the overseas subsidiary of the Indian parent company borrowed at a rate higher than the prescribed ceiling. The parent company contended that it did not violate ECB guidelines since it did not directly borrow in foreign currency, but rather its subsidiary (which happened to be a foreign entity) was the one borrowing foreign currency. However, the overseas subsidiary was only a shell company and the onus of repayment and debt servicing was on the Indian parent company. So in effect, it meant that the Indian company raised foreign currency borrowing at a rate higher than the ECB prescription.

Policy framework and regulations on foreign currency borrowings by Indian companies

The regulation on the interest rate ceiling for the Indian companies availing ECB applicable at that time was specified in the RBI Master Circular (Reserve Bank of India, 2014) which, *inter alia*, specified that:

> All-in-cost includes rate of interest, other fees and expenses in foreign currency except commitment fee, pre-payment fee, and fees payable in Indian Rupees. The payment of withholding tax in Indian Rupees is excluded for calculating the all-in-cost.
>
> With the existing all-in-cost ceilings for ECB as follows:

Average Maturity Period	**All-in-cost ceilings over 6-month LIBOR***
Three years, and up to 5 years	350 basis points
More than 5 years	500 basis points

*For the respective currency of borrowing or applicable benchmark

It may be noticed that the company—through its subsidiary—raised foreign currency borrowing at a higher rate and violated the ECB regulations by issuing an Indian Rupee-denominated bond which, in turn, was subscribed by its own subsidiary using foreign currency funds. This convoluted structure was adopted as there was not a similar restriction on the interest rate ceiling on the local currency bond. If we analyze the structure of the borrowing, it may be observed that the Indian company was able to raise foreign currency debt, which it otherwise would not have been eligible to raise. It had to pay an interest rate of 8%, which was above the Reserve Bank of India's prescribed ceiling. Since, the company was relatively new and small, it had to offer a higher rate of interest to entice the foreign investors into investing in its bonds. The rationale of having interest rate ceilings on foreign currency borrowings is to restrict such borrowings only to companies with better credit ratings. The companies with good ratings would be in a better position to repay their debt. In this case, although Greenko Group tried to camouflage the borrowings, foreign currency risk resided on its balance sheet, which can be a cause of concern for itself as well as for the country from macroeconomic stability perspective. A new company (like Greenko Group) or a company with an inferior rating would necessarily have to pay higher credit risk premium for borrowing foreign currency. There were media reports about many other firms (also engaged in the renewable energy space) attempting to borrow from overseas via similar modus-operandi. Hence, regulations were subsequently modified in order to avoid continued, similar incidences.

It is possible that many other developing nations, which have similarly restricted capital account convertibility, would control overseas borrowings from a macro-stability point of view. Therefore, for many firms, this channel of borrowing may not be forthcoming. Moreover, as previously mentioned, such sources may not work out to be more affordable for a firm without high credit rating. Since many RE firms in developing nations are relatively new, it is likely that their credit rating is not yet high enough to bargain a lower interest rate in the global financial market. Due to these limitations that small RE companies face, developing nations must think of innovative ways to help such firms access stable and cost-effective finance for RE projects.

Possible Solutions

Issuance of local currency bonds in the overseas market Indian companies have now been permitted to raise borrowings from overseas markets by issuing bonds denominated in the local currency, commonly known as 'Masala Bonds' (Reserve Bank of India, 2015). These types of bonds enable Indian companies to raise foreign currency loans without being exposed to currency exchange fluctuation risks. Since these bonds will be denominated in Indian Rupee, it will be the foreign investors of the bonds who will have to bear the currency risk. Several Indian companies, including energy companies, have floated such bonds and raised finance from the overseas market. In fact, the Indian Renewable Energy Development Agency (IREDA) raised $300 million (USD) by issuing Masala Bonds for the purpose of extending financial support to firms engaged in RE. Therefore, this type of financing has demonstrated how it can play a very important role in mobilizing funds from overseas market.

Local currency financing by international financing institutions like International Finance Corporation (IFC) These entities provide long-term financing for projects relating to infrastructure development, including RE, in many developing nations. IFC has programs across the world that address the development of sustainable energy. IFC has invested in bonds of firms engaged in this field in many countries, including Indonesia and China (International Finance Corporation, n.d.). IFC, by virtue of its topnotch ratings, has been able to raise funds globally at a relatively lower rate, which it then lends to projects in member nations. This channel can also be tapped by developing nations to obtain funds for their local firms—and in countries where such facilities are available, they need to be extensively promoted.

Tax-free bonds Local governments may consider providing tax incentives to citizens who invest in bonds issued by RE companies. While such a move may not be viewed positively from a government's fiscal perspective, the positive externalities generated by RE can offset these costs at a later stage.

Incentivizing long-term investors to invest in bonds issued by RE firms or agencies involved in RE financing Since RE projects are long-term investments, pension funds may utilize the bonds issued by RE firms or even by the related agencies (which are involved in RE financing) from asset-liability matching. In order to make them more attractive for such investors, governments may consider providing some kind of guarantees on these bonds. Such sovereign guarantees could make these bonds attractive, even for foreign pension funds.

Asset-backed securities Though these types of securities received a bad reputation after the 2007 financial crisis, they can be very potent tools for mobilizing resources by tying the future receivables to the securities (via the process of securitization).

Conclusion

The importance of RE sources in developing nations cannot be understated and there is increasing need for concerted efforts on the part of all stakeholders to ensure sustainable energy generation in a cost-effective manner. Only then will firms and individuals wean away from fossil fuels and shift to RE sources. But for keeping the cost of production of RE low there has to be abundant supply of funds to this sector, which is possible if more players participate and innovative financing products are made available. From the entire gamut, this write-up has tried to analyze one specific issue relating to constraints in respect of debt financing and associated possible policy solutions. Developing nations may find some of the above solutions as viable options for their green mission.

Water, Sanitation, and Energy Balance: An Investigation of System Performance in Cebu, Philippines

Brandon Hunter

Brandon Hunter (brandon.hunter@duke.edu) is an Environmental Engineering doctoral candidate at Duke University's Pratt School of Engineering

Keywords: sanitation, anaerobic digestion, biogas, pasteurization

In 2017, the World Health Organization estimated that 2.3 billion people, nearly one third of the global population, lack access to improved sanitation facilities (i.e., facilities in which waste is adequately contained, removed from direct human exposure, and the waste is treated). Of this demographic, about 900 million people practice open defecation, which neither removes nor treats excreta (UNICEF and WHO, 2017). Unimproved sanitation options, such as pit latrines, succeed in separating people from waste but do not treat waste before discharging it into the environment. In fact, about 60% of all fecal waste globally does not undergo any type of treatment (Baum et al., 2013). Due to this lack of treatment, it is estimated that over 50% of all rivers, oceans, and lakes are contaminated with untreated wastewater (Mara, 2004). Globally, approximately 2 billion people drink water from sources polluted with feces (UN ECOSOC, 2016; WHO, 2018).

Every year, food and water contaminated with fecal matter are estimated to cause over 2.5 billion diarrheal cases in children five years old or younger, resulting in over 1.5 million child deaths per year (Bill & Melinda Gates Foundation, 2012). In addition to contributing to the spread of disease, untreated human waste contains high levels of organic matter that may lead to anaerobic conditions, which inhibit and can kill aquatic and terrestrial life, compromising ecosystems in affected areas. Untreated waste can also leach through soil and contaminate groundwater. Lack of access to improved sanitation has also been shown to negatively impact the economy. It is estimated that for every $1 USD invested in access to improved water and sanitation, $4.30 USD is generated in economic returns through increased productivity (UNICEF and WHO, 2017). For example, the World Bank estimates that inadequate sanitation is responsible for a loss of 6.4% of India's GDP (United Nations, 2015). Understanding the dire need to incorporate treatment into sanitation solutions, the United Nations currently aims to achieve universal access to improved sanitation by 2030 (United Nations, 2015).

This goal would ideally be met by implementing piped sewer systems, but in many access-deprived areas this proves financially and logistically challenging. Hence, many areas around the world have adopted decentralized on-site sanitation (OSS) as an effective means to increase basic sanitation access. In fact, OSS facilities provide access to 35% of the global population, predominately serving those in lower income areas. In urban areas of Ghana and the Philippines, for example, about 85% and 98% of households utilize on-site treatment facilities, respectively (Montangero and Strauss, 2004). On-site technologies are also estimated to account for 65–100% of all sanitation access in sub-Saharan Africa (Strande, 2014). There is significant need to improve these technologies by incorporating adequate waste treatment, as the portion of the world which relies on OSS facilities is expected to nearly double to 66% of the global population (i.e., 5 billion people) by 2030 (Strande, 2014).

An Improved On-Site Sanitation (OSS) System

To help meet this need for improved on-site sanitation systems, Dr. Marc Deshusses, Professor of Civil and Environmental Engineering at Duke University, conceptualized an OSS technology now known as the Anaerobic Digestion Pasteurization Latrine (ADPL). The ADPL system uses anaerobic digestion of human waste to generate biogas, which is then ignited to treat the effluent via pasteurization, making the entire process energy neutral. The ADPL system is self-contained, operates by gravity flow, requires little maintenance and operation, and is constructed using local resources (Colón et al., 2015). The ADPL system has also been demonstrated to be effective without incorporating any moving parts. This makes the ADPL system robust, as moving system parts often lead to failure in the field—more parts mean more pieces that could break or malfunction.

The overall goal of the research project (funded by the Bill & Melinda Gates Foundation) is to provide low-resource communities with an improved sanitation system that costs less than $0.05 USD per person per day. Since 2013, a total of five fully operational pilot units have been deployed across Kenya, India, and the Philippines. Locations were selected for several reasons including (but not limited to) sanitation need in the region, availability of labor to install field units, locally sourced materials, mutual interest from partner organizations, dedication from partner organizations, and social sustainability (i.e., the compatibility of the social context in which the technology would be implemented).

I serve as the Duke ADPL team liaison to our partners in the Philippines and oversee the operations of the systems there. Since I have been involved with the design, installation, and operations of ADPL systems in the Philippines, the focus of this case study will be on the systems there, rather than our Kenyan and Indian systems. Hence, the reflections herein are unique to ADPL field units located throughout the mountainous rural barangays (villages) of Toledo City, Cebu, Philippines. My goal in writing this case study is to develop a more thorough understanding of the cultural and environmental contexts in which the ADPL units are implemented in the Philippines, and to offer insights on how these contexts may also impact other remotely-designed systems. Even the most cost-effective and high performing state-of-the-art technologies, if implemented in the improper context, are vulnerable to failure. I hope that this information will lead to more efficient and effective engineered systems that carefully consider the culture and environment of its users.

System Description

Like many pour-flush toilet systems, the inputs for the ADPL include urine, excrement, and the water used for flushing. The ADPL was first designed to operate according to the assumption that an adult typically excretes ~1 liter of urine and ~400 grams of feces per day (Franceys et al., 1992), and that ~1 liter of water was sufficient to flush the feces/urine through the system. The waste streams are gravity fed and the flush water transports the waste from the toilet bowl, through a pipe, and into the anaerobic digester. Microbes in the anaerobic digester consume most of the solid organic compounds in the waste stream, converting them into methane-rich biogas. The liquid waste stream exits the anaerobic digester and enters a conventional tube heat exchanger where it is preheated before entering a heater for treatment (pasteurization). This treated stream is then cycled back over the outer shell of the heat exchanger to preheat the next wave of incoming liquid.

While in the heater, the waste stream is heated to 65–75 °C for 2 hours to inactivate all pathogens. This pasteurization process, of course, requires energy, which is fueled by the burning of the energy-rich biogas generated by the microbes in the digester, and making the entire waste treatment process energy neutral. There are additional potential benefits from using the ADPL system in settings where excess biogas is generated, as the excess biogas can be piped off for additional energy applications including use for lighting or as cooking fuel. The overall ADPL waste treatment proccess is depicted in a schematic (Figure 6).

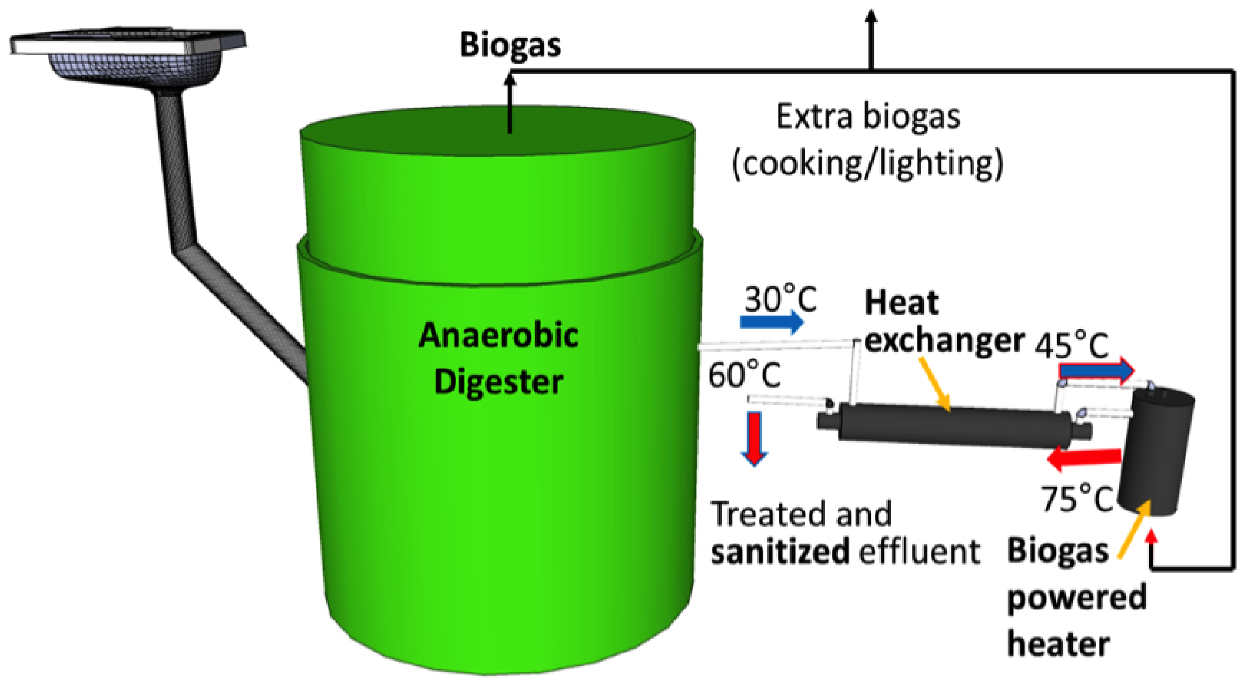

Figure 6: Schematic of the wastewater treatment processes in the ADPL (anaerobic digestion pasteurization latrine)

Field Performance - Cultural Practices

The ADPL process can be energy neutral because microbes convert organics from feces/urine into the biogas that is used to treat that same feces/urine. The added flush water dilutes the organics that microbes need for energy, but the system was designed to operate with ~1 liter of water per flush (which, again, is the typically assumed reference value used to estimate how much water a person will use to flush away their feces/urine). This 1-liter assumption held true for prior field tests in Kenya. However, this was not the case for ADPL systems in the Philippines.

In July 2016, our Duke ADPL team traveled to the Philippines and met with our partners, the Tesari Foundation, to complete the installation of two pilot systems. The concrete foundation and support structures had already been built, the toilets were installed, the digesters were placed on site, and the heating systems were newly fabricated. Our trip goals were to connect all of these components together, install an integrative control system, and begin operating the anaerobic digesters. We were also traveling with a Duke undergraduate student who performed a social evaluation of the community, which documented how users interacted with the ADPL systems. These survey evaluations—which were not reviewed until after the team had returned to the States—revealed something unexpected: users in the Philippines typically used more than 1 liter of water per visit to the restroom.

In Kenya (as in the United States) it is customary for people to wipe to clean themselves after defecating. Water is then used to flush the wiping material down the toilet along with the feces/urine. However, for the communities at the Philippines ADPL sites, wiping is not customary. Instead, people clean themselves by washing with water after defecating. Since water was used for both flushing and for cleaning, on average there was more than the presumed 1 liter of water (which the ADPL system was designed to handle) entering the system after each use. The system, therefore, was likely unable to properly treat the waste stream: the excess water would increase the total volume of waste stream that needs to be treated, without increasing the organic content which provides the energy (i.e., enough biogas) needed to do so. According to readouts of performance data, the ADPL systems were generally operating as expected: the anaerobic digesters were still producing biogas, that biogas was still being burned and used as heat, and the waste stream was still being heated—however, there was insufficient energy to consistently heat this larger volume of waste stream to the safe target temperature range.

Remotely Calculating Excess Water Input

The low temperature data suggested that there was too much water being added to the system for the waste to be properly treated. Results from the previously mentioned social survey (regarding the use of additional water for washing) also supported the hypothesis that the below-target temperatures were a result of excess water entering the system. In order to diagnose how the excess water was impacting system performance, the volume of this additional water needed to be determined. To do so, first the entire combined flow (urine, feces, flush/washing water) needed to be estimated. The total waste stream flowing through the system was determined using a simple 'bucket tipping method' (designed in 2016), which operates as follows: the waste stream is piped into a bucket that tips over when full due to gravity and pours out its contents. Every time the bucket tips, a magnet (attached to the bucket's exterior wall) passes by a sensor, which counts the number of times the bucket tips. Knowing the volume that causes the bucket to tip and knowing the total number of tips for any given period, the total flow rate of combined waste can be calculated. After accounting for how much waste people typically generate (which can be derived from the amount of biogas produced, as described below), our team was able to determine how much total water was being used, on average, for combined flushing and washing purposes.

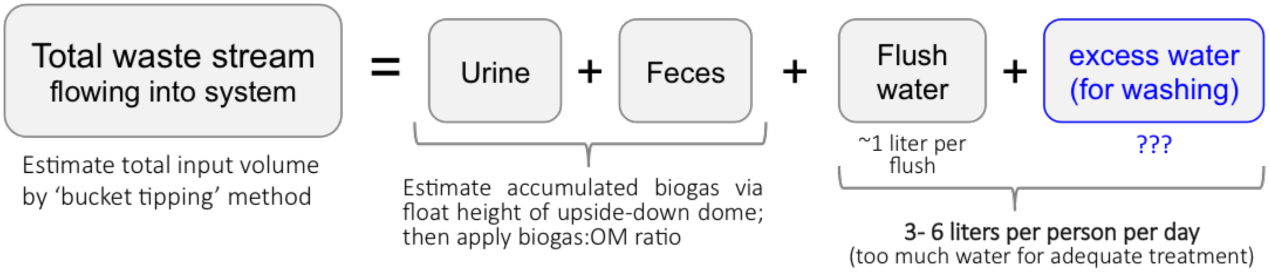

Figure 7: The diagram above summarizes how to calculate the waste stream components flowing into the ADPL (on a per person per day basis). To estimate the excess water for washing (in blue), the other components of the incoming waste stream must first be determined.

To estimate the input of urine and feces, the amount of biogas generated by the system needed to be remotely estimated. To describe the process briefly, the biogas generated in the anaerobic digester is transferred through tubing into a floating biogas dome. The mechanism works by displacement: a large drum is filled with water and another drum with a slightly smaller diameter is placed into the water upside down, creating a floating dome that traps and accumulates biogas (biogas rises and collects in the upside-down dome since it is lighter than the water beneath it). As the biogas volume accumulates in the upside-down drum, it forces the upside-down dome upwards, causing it to float in the water. The increase in dome height corresponds to an increase in biogas volume. Hence, the volume of biogas generated and stored by the anaerobic digester can be calculated.

By knowing the amount of biogas, we can estimate how much urine/feces enter the system (using a biogas to organic matter ratio; and assumptions on how much organic matter is in urine and feces). Assuming only feces, urine, and water are inputs, the volume of water can be calculated as summarized in Figure 7. The total amount of water used for both flushing and washing was calculated to be between 3–6 liters per person per day, which is beyond the operable energy-to-volume ratio threshold that would properly pasteurize the entire waste stream.

Of the total daily water input, it is difficult to reliably attribute how much water is used for flushing versus used for washing. For this reason, we thought it would be beneficial to integrate a toilet that only needed a fixed amount of water to flush, thus potentially controlling the amount of flush water used. In 2017, our Duke team traveled to the Philippines again and updated the systems with various developments made over the previous year. These updates included the installation of new low-flush toilets that were donated by EnviroSan, a South African toilet manufacturer (the toilets are designed such that waste can be flushed down with a fixed 1-liter volume of water). Unfortunately, the stalls were designed and constructed to accommodate small, seated toilets, and the EnviroSan toilets required additional floor space due to the low-flush

Figure 8: Photo of an ADPL system in Baragay Sagay, Toledo City, Cebu, Philippines. This view highlights the back of the latrine where the treatment system is located (the latrine entrance cannot be seen from this angle).

attachment at the back of the toilet. Due to the limited legroom, the decision was made to only install the toilet bowl itself. However, without the low-flush attachment, we were ultimately unable to differentiate between the amount of water used for flushing versus washing.

The ADPL currently cannot ensure proper biogas-powered pasteurization of the entire waste stream given the high levels of water input by its users, making the ADPL units in the Philippines the only Duke ADPL systems that do not produce the necessary amount of energy required for treatment. To address this energy deficit, our upcoming field visits will explore the potential to supplement the biogas with the addition of solar heating. Also, the pasteurization system will be redesigned to increase heat transfer efficiencies for the Philippine context.

Field Performance - Environmental Factors

During the rainy seasons in the Philippines, it rains almost every day and there is an abundance of water. The ADPL system takes advantage of frequent rainfall by collecting runoff from the ADPL roof and storing it in rain barrels; this stored rainwater is then used as flush and wash water. However, during the dry season, water scarcity is a threat to users in the Philippines. Water is more difficult to come by in the mountainous rural barangays of Toledo City, sometimes causing people to purchase bottled water for flushing and washing. Based on an updated social survey during the 2017 trip, ADPL users were open to reusing the treated wastewater as long as quality standards were achieved. The Duke team has conducted various laboratory and field experiments on further treating waste (after anaerobic digestion) with post-treatment filters to remove more organics and nutrient contaminants. Based on the results of those studies, I am currently investigating the possibility of reusing treated effluent as flush water and the possibility of simultaneously recovering nutrients in the waste to be reused as a fertilizer.

Conclusion

Working on this project has been a firm reminder that a lot of work and planning are required to convert a laboratory research experiment into a full-scale field unit which is consistently used by people (Figure 8). Human behavior varies significantly and user interaction with an engineering field unit is rarely predictable. Instead of expecting stakeholders to change behaviors and adapt to a technology, it is more important to develop technologies that cater to the customary practices of those who will interact with it. The environmental, economic, social, and cultural differences among the diverse ADPL field unit locations add complexity to the design and operation, emphasizing the importance of system adaptability to human-centered design. The Duke ADPL team has designed a new iteration of the system, which we plan to install and operate in Toledo City, Cebu, Philippines in 2019. We are excited for the opportunity to use our findings to create a further improved sanitation system that more closely aligns with the behavioral patterns of its users as well as with the environmental conditions that we have observed in the Philippines. It is my hope that this case study will aide in preparing other engineering research design teams to develop their technologies with considerations for the specific environmental, economic, social, and cultural contexts in which their technology will ultimately be used.

Building the Case for Improved Cookstoves in Mandena, Madagascar

THOMAS KLUG

Thomas Klug (thomas.klug@duke.edu) was an undergraduate student at Duke University at the time of writing of this case study. He graduated in 2018 with a B.A. in Public Policy and a B.S. in Environmental Science.

IN MADAGASCAR, 99% of the total population depends on biomass fuels (such as wood, charcoal, dung, and crop waste) for cooking (Dasgupta et al., 2015). Burning biomass fuel contributes to household air pollution (HAP), which is linked to COPD, ischemic heart disease, and lower respiratory tract infections (Lim et al., 2012). Lower respiratory tract infections are the second leading cause of death in Madagascar, after diarrheal diseases (Dasgupta et al., 2015), and HAP was the second most important risk factor contributing to DALYs ('disability-adjusted life years,' a metric for one lost year of 'healthy' life) in Sub-Saharan Africa in 2010 (World Bank, 2014). Despite HAP being a major risk factor for disease and disability in Madagascar, the island has one of the lowest market penetration rates of modern fuels (<1% of the population) among Sub-Saharan African countries (World Bank, 2014).

The demand for fuelwood leads to environmental degradation and deforestation, contributing to the loss of endemic plants and animals. In the town of Toliara (in southwest Madagascar), use of charcoal fuel was estimated to destroy 80 million square meters (nearly 20,000 acres) of forest each year (Ramampiherika, 1999). More recent research contends that fuelwood collection more often results in forest degradation, where only selected parts of trees are removed (Casse et al., 2004), but both forest degradation and destruction contribute to biodiversity loss. In fact, nearly 10% of the island's endemic plant and animal species went extinct between 1950 and 2000 (Allnutt et al., 2008).

To investigate the role of biomass fuels on HAP and the environment, I spent 1 month collecting survey data and personal exposure measurements in the village of Mandena, in the SAVA (Sambava-Andapa-Vohemar-Antalaha) region of Madagascar during summer 2017. I spent an additional month in the town of Sambava (one of the four major towns in the region) assessing performance of improved cookstoves and their potential to mitigate emissions. The objectives outlined for me and my team of Duke University undergraduate and Master's students were to:

1. Estimate the burden of fuelwood use/collection on individuals and the environment
2. Quantify household air pollution (HAP), including exposure to particulate matter ($\mathrm{PM}_{2.5}$) and carbon monoxide (CO)
3. Explore the impacts of HAP on blood pressure and lung capacity
4. Estimate the fuel savings potential of locally-made improved biomass stoves

In this case study, I first present objectives 1-3 using a variety of qualitative and quantitative data gathered by my team in Mandena. Then, to address the fourth and final objective, I present an assessment of different types of locally-made improved cookstoves, which were tested with the Duke Lemur Center (DLC) SAVA Conservation Initiative in Sambava. Based on these insights, I propose recommendations for the DLC's improved cookstove initiative, community stakeholders, and future researchers.

Study population and community characteristics

As mentioned, the first month of research aimed to examine health and environmental impacts from biomass fuel-use in Mandena, a village that lies between two major cities in the SAVA region (Sambava and Andapa) and has a population of about 2,200 people. The households participating in this research ($N = 37$) were randomly selected to take part in a one-month study on household cooking practices. Of the households surveyed, we observed that households typically consist of five members, and that most households engage in subsistence agriculture and cash crop production of vanilla for food and income. Lacking access to modern fuels such as liquefied petroleum gas (LPG) and electricity, residents living in Mandena rely on solid biomass fuels (typically wood, but sometimes charcoal) to meet household cooking needs. Primary cooks (almost exclusively women) varied in age from 21 to 69, with an average age just under 40 years old. Although the vast majority of primary cooks are women, we found that fuelwood collection is almost exclusively performed by adult males on personally-owned or family-owned land, unlike most Sub-Saharan African countries where fuelwood collection is usually tasked to women (World Bank, 2014). Most households in Mandena have a separate kitchen space (with four walls, a door, and a roof) constructed adjacent to the primary residence. Depending on the size of these structures, families may eat meals inside together. None of the kitchens were vented or included any type of chimney structure.

It should be noted that community characteristics/generalizations suggested by household surveys were further supported by focus group discussions with eight randomly selected primary cooks from outside our household sample.

Objective 1: Estimate the burden of fuelwood use/collection on individuals and the environment

Burden of fuelwood collection

Male fuelwood collectors ($N = 21$) from our household sample were surveyed on the potential burdens associated with collecting fuelwood. Participants reported traveling $\sim$3 km three times per week on average to collect fuelwood, and around a third of participants reported having to travel further for wood than last year. Primary cooks from focus group discussions also expressed concerns about fuelwood scarcity, and several women reported planting new trees on their land to secure these resources for the future.

Indeed, the deforestation and landscape degradation around Mandena is striking, particularly given the village's location on the outskirts of the near-pristine Marojejy National Park. In addition to the community's reliance on the surrounding land for agriculture, pastoralism, construction materials and other resources, households consume an average of 8.5 kg of fuelwood per day, translating to an estimated 3,000 kg of wood for cooking per household each year (assuming our estimated daily rates are typical). Per household, average fuelwood consumption was effectively the same for lunch and dinner (3.21 ± 2.22 and 3.14 ± 2.26 kg of fuelwood, respectively), and breakfast fuel consumption was notably lower (2.26 ± 1.78 kg of fuelwood).

Burden of fuelwood use

Based on results from community surveys and focus group discussions, nearly all households (95%) reported regularly cooking with traditional stoves such as metal tripods or three-stone fires. About half of the primary cooks surveyed reported having other family members in the kitchen with them while they cooked; in particular, 14 of 37 households reported having at least one child in the kitchen with them while cooking. Focus group discussions indicated that many primary cooks are aware of—and prefer to cook using—certain species of wood that produce less smoke when burned. From our household survey, over 70% were aware of various tree species that produced less smoke and preferred to use them when available. Around 40% of households reported owning an improved cookstove, but also stated that these were only used intermittently for special events or when charcoal was cheaper or more readily available. Focus group participants expressed favorable interest in adopting an improved cookstove or an alternative fuel to reduce the smoke in their kitchens. However, participants cited price and access to markets as major barriers to adoption.

Objective 2: Quantify household air pollution (HAP), including exposure to particulate matter ($PM_{2.5}$) and carbon monoxide (CO)

Quantifying exposure to HAP

Figure 9: Primary cook wearing backpack sampler in Mandena, Madagascar

Primary cooks are subject to high exposures from biomass fuel emissions. To estimate typical exposure levels, we provided primary cooks (N = 23) with backpack samplers (Figure 9), which housed monitoring devices used to measure real-time 1-minute-averaged concentrations of carbon monoxide (CO) and particulate matter ($\mathrm{PM}_{2.5}$; particles <2.5 microns in diameter). Participants wore the backpack sampler for a 24-hour duration. In addition to pollutant exposure data, we also obtained a host of measured and self-reported health data from study participants.

Exposure to air pollutants (including CO and $\mathrm{PM}_{2.5}$) is linked to both chronic and acute health effects, including respiratory disease, pregnancy complications, nausea, dizziness, and even death (Smith et al., 2014). Figure 10 displays the distribution of 24-hour averaged $\mathrm{PM}_{2.5}$ levels measured by the backpack samplers. CO levels are not displayed as 1-minute-averaged concentrations were generally low. However, because CO fluctuates rapidly during combustion, measuring at a briefer time interval (such as 10-second or 30-second intervals) would likely result in higher reported CO data. The $\mathrm{PM}_{2.5}$ distributions can be thought of as an estimate of typical daily exposures for primary cooks in Mandena. Nearly 80% of households exceed the World Health Organization's daily $\mathrm{PM}_{2.5}$ limit of 25 μg/m3 (represented as a red dashed line in Figure 10).

Figure 11 shows how PM accumulates over the day. Plateauing indicates times when there were not significant sources of PM contributing to the individual's exposure, while steep increases represent events where PM levels were high. The three distinct step increases that are visible in Figure 11 are attributed to cooking during lunch, dinner, and breakfast, in that order. These results make it clear that the overwhelming majority

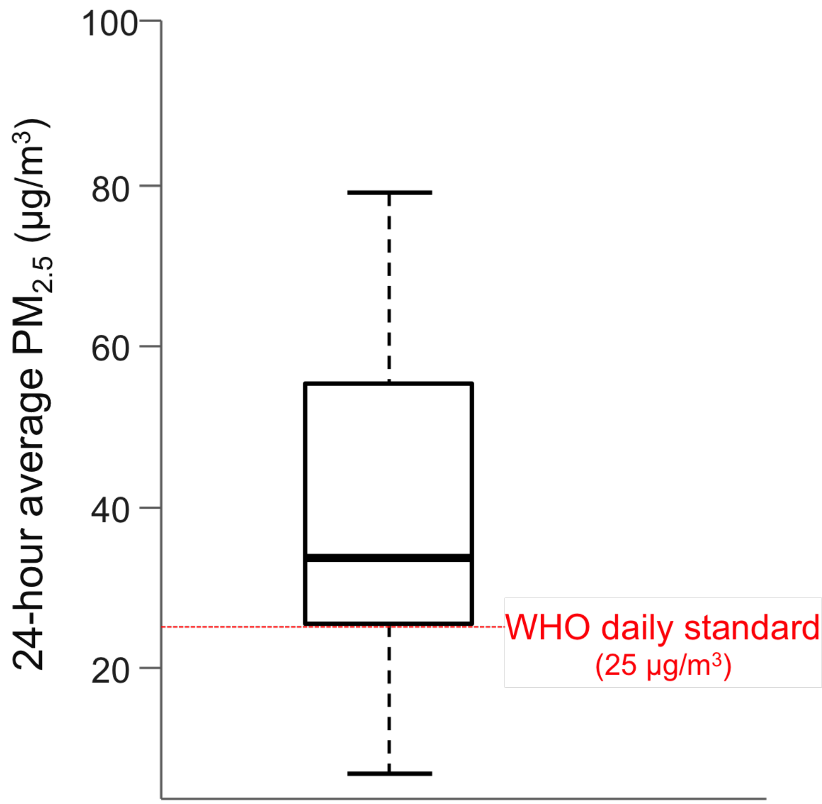

Figure 10: Distribution of 24-hour averaged $\mathrm{PM}_{2.5}$ levels measured by exposure monitoring backpack worn by $N = 23$ study participants. The 24-hour average $\mathrm{PM}_{2.5}$ WHO standard is highlighted by the red dotted line. The boxplot represents the median, and 25$^{\mathrm{th}}$ and 75$^{\mathrm{th}}$ percentiles.

of daily $\mathrm{PM}_{2.5}$ exposure is attributed to cooking emissions.

Fuelwood dried above the fire before use (~64% of households) produced half as much CO on average, and 10 μg/m3 less $\mathrm{PM}_{2.5}$ per 24-hours, on average than fuelwood that was not, suggesting that (as expected) dryer wood produces fewer emissions when burned. We also observed that, unsurprisingly, cooks who used more wood were exposed to statistically significant greater levels of pollutants overall. Though these results were not unexpected, they are still important to confirm when considering the potential health impacts of improved cookstoves, which often operate with lower fuel inputs compared to traditional methods.

Objective 3: Explore the impacts of HAP on blood pressure and lung capacity

Estimating health impacts

At the end of the 24-hour period, participants who wore the exposure monitoring backpacks had their blood pressure measured three times consecutively. Previous studies, such as Alexander et al. (2014), have

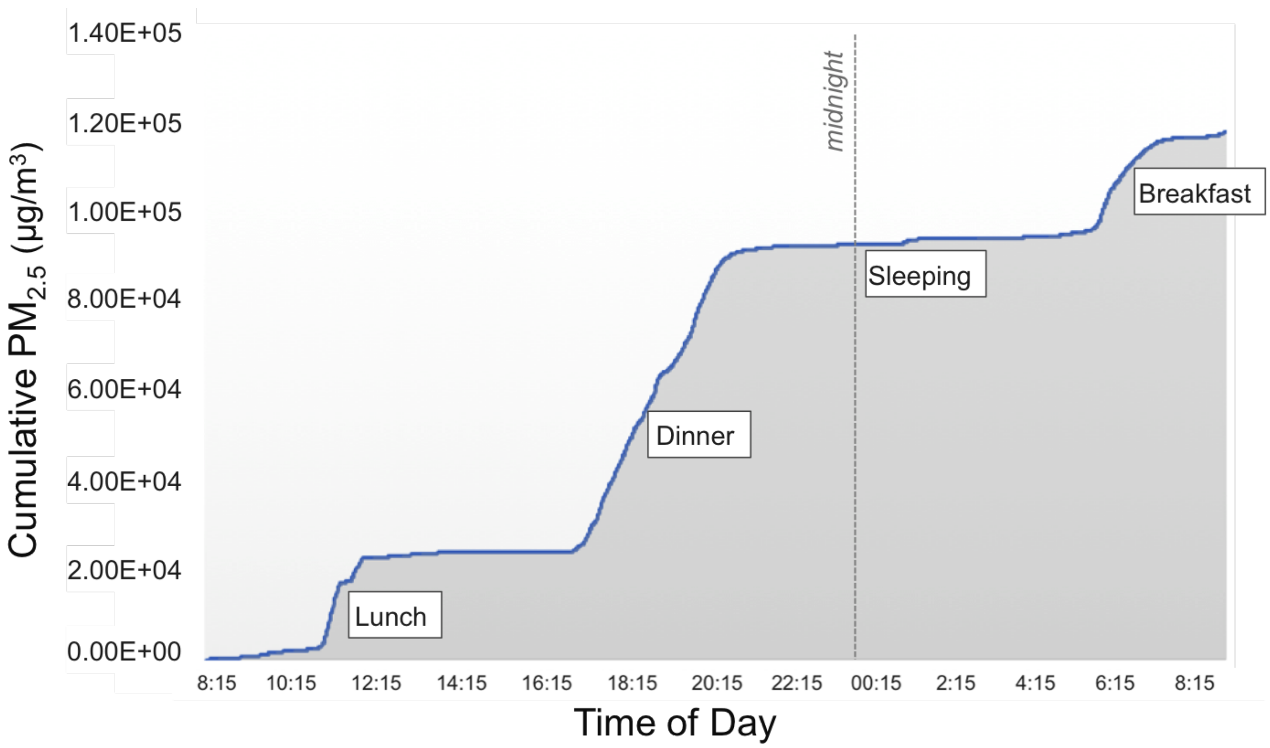

Figure 11: Cumulative $PM_{2.5}$ accumulated over a 24-hour period. The increasing slopes represent cooking periods where PM emissions increased.

demonstrated how improved cookstove use can have positive implications for HAP and blood pressure, though blood measurements from our study were not significantly correlated with PM ($r = 0.31$) or CO ($r = 0.36$). Community-wide data suggest that 42% of participants suffer from hypertension and revealed that women are more likely to be hypertensive than men for all age groups (based on the 2017 guidelines from the American College of Cardiology and American Heart Association (Whelton et al., 2017)). Also, spirometry measurements suggest that 1 in 5 participants have impaired lung function. Household surveys ($N = 20$) indicate that 79% of respondents reported at least one member of their family had a cough or runny nose within two weeks before the survey was administered.

Objective 4: Estimate the fuel savings potential of locally-made improved biomass stoves

Overview of improved cookstoves in the SAVA region

Penetration of LPG fuels is low and electricity access in the SAVA region is limited. Without developed energy infrastructure, households are heavily reliant on biomass fuels for their daily energy needs. In the ab-

Figure 12: Four examples of improved biomass cookstoves manufactured in the SAVA region are shown. The first stove on the left (the "Red Multi Stove") is one of the few wood fuel models available.

sence of clean fuels, cookstove markets are restricted to biomass-burning stoves. There are few improved biomass cookstoves manufactured and sold in the SAVA region, and most of the existing businesses are small-scale and employ no additional workers. A survey of 18 of these local manufacturers reveals that seven sell door-to-door or on an as-ordered basis, and six sell in larger, town markets. In addition to being extremely localized, the improved cookstove market is virtually exclusive to charcoal-burning stoves, with only two (out of 18) actively selling wood-burning models. While charcoal produces less HAP when burned, charcoal is more expensive than wood and not widely accessible in rural regions (like Mandena). Individuals who can afford to cook with charcoal are also more likely to have the purchasing power to invest in improved stoves.

Among the producers surveyed, stove manufacturing materials are relatively uniform. These materials include clay, concrete, sheet metal, sand, and/or dung. Despite this uniformity, there is a dizzying array of diversity in stove design and innovation. While there are a few similar models, stoves were made in all shapes and sizes (with many sellers offering multiple sizes of the same model to accommodate different cooking capacities). Design innovations were made, including improved drafting for the combustion chamber, removable ash trays, fuel storage drawers, pot skirts, and features to facilitate portability and durability. Figure 12 shows a few of these unique models. The average market price of the stoves was about 13,000 Ariary ($4.30 USD) and average cost of production was 2,500 Ariary ($0.83 USD). The average Malagasy makes less than $1/day, making investment in an improved cookstove infeasible for many without savings or financing options (World Data, 2016).

Improved cookstove testing

Several of these stoves were purchased in order to run comparative tests. One prevalent cookstove test is the "water boiling test." This test is meant to compare fuel consumption and cooking speed of each stove type by assessing the amount of fuel and time taken for a stove to boil

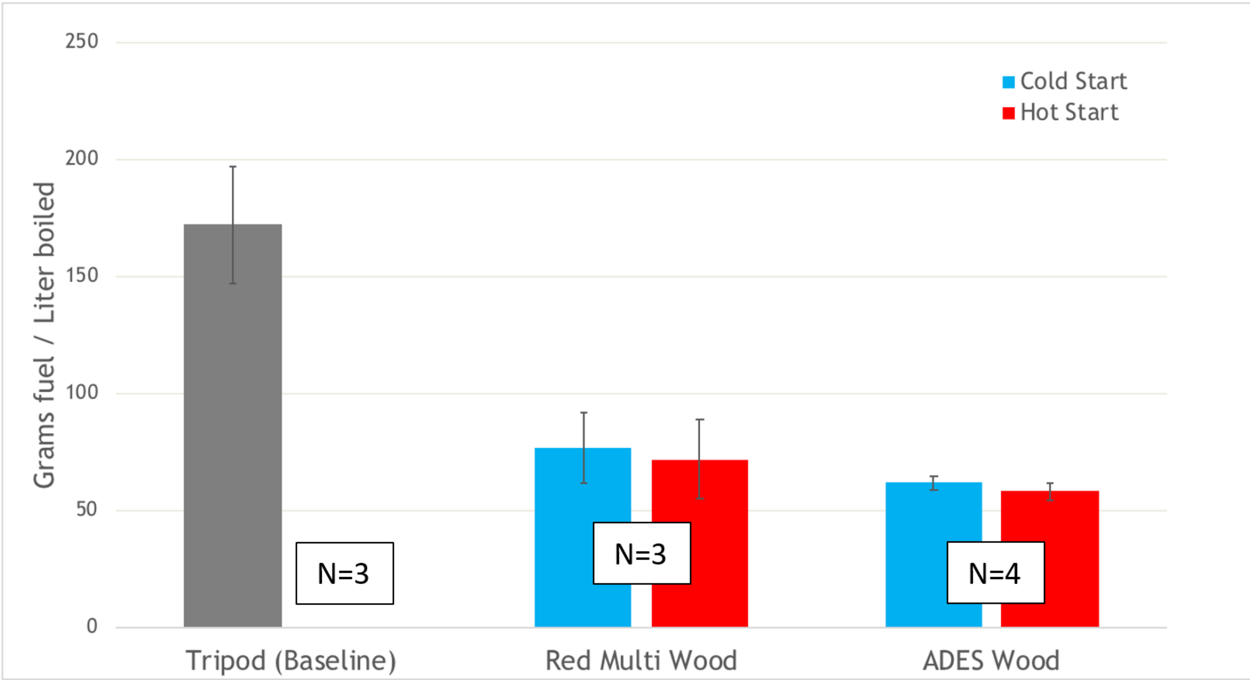

Figure 13: Specific fuel consumption for wood stoves (measured in weight of fuel consumed per liter of water boiled)

a 2.5-liter pot of water. Tests were conducted in an outdoor kitchen setup near the DLC's office in Sambava. Two standardized tests (the cold start and hot start tests) were repeated a minimum of three times per stove. The cold start test involves boiling water when the stove is at room temperature (i.e., has not been recently used and therefore has no residual heat), while the hot start test involves boiling water when the stove is still warm from prior use. For cold and hot start tests, fuel consumption was calculated and mean results were compared. Though these tests only quantify boiling time and fuel efficiency, they are two of the most important factors determining the uptake of an improved cookstove, as emphasized by participants in our focus group discussions.

Improved stoves were compared to the traditional method of metal tripod cooking, which uses an open-fire to heat a pot that is supported by a tripod. With this traditional tripod method as a baseline for comparison, baseline results were compared against results from the two improved wood-burning stoves (recall that only two of the 18 improved stoves use wood fuel, rather than charcoal): the "Red Multi Stove," which is a locally-made model; and the "ADES Wood" stove, which is manufactured in the capital city of Madagascar and shipped to the SAVA for sale and distribution by the DLC.

Results for fuel consumption during the cold and hot start phases of the test for the wood-burning stoves are summarized in Figure 13.

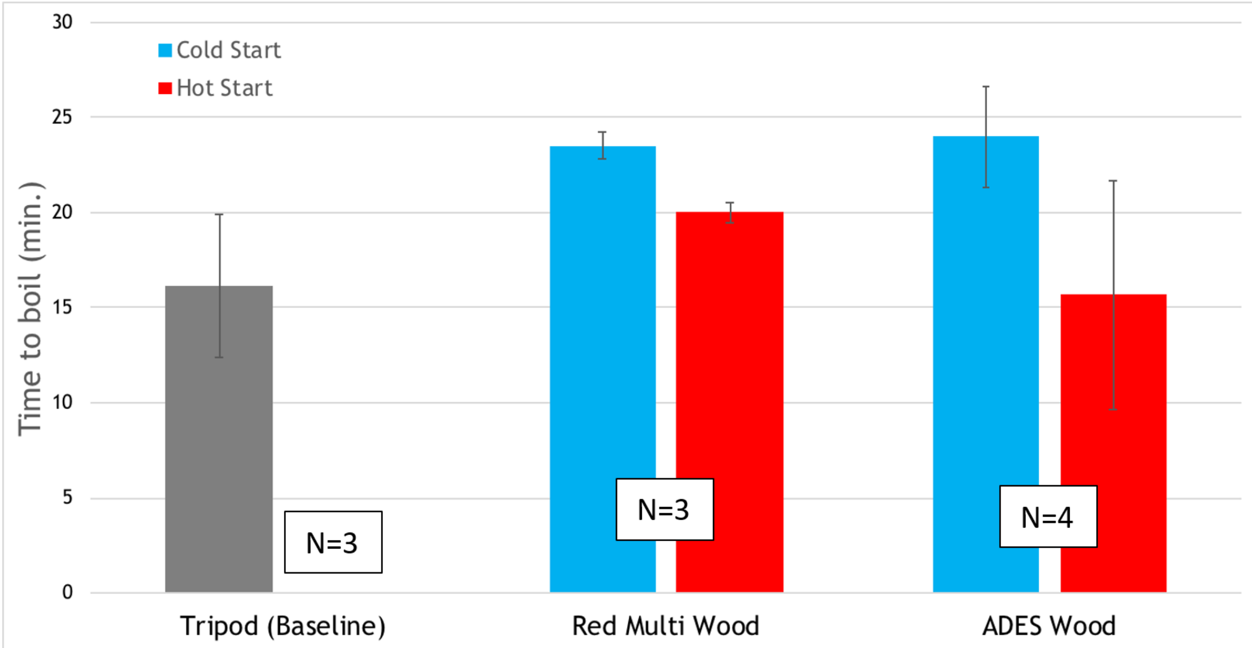

Figure 14: Time to boil for wood stoves

Note that hot start tests were not applicable for the tripod stove since there is not an insulated stove to retain heat. Mean fuel consumption for both the Red Multi stove and ADES Wood stove were statistically significantly lower than the tripod stove. In fact, to heat the same volume of water, the improved wood stoves used less than half of the wood fuel consumed by the baseline tripod method. Figure 14 indicates the average time to boil during the cold and hot start phases of the tests. For hot start tests, the ADES boils water ∼1 minute faster than the baseline tripod method. However, for cold start tests the ADES takes nearly 10 minutes longer to boil water compared to baseline. The Red Multi stove takes ∼4 and ∼8 minutes longer to boil water (for hot and cold tests, respectively) compared to the baseline tripod method. These data reveal large differences in fuel consumption between improved stoves and baseline tripod performance, though this comes at the cost of added cooking time. Though more dynamic tests should be applied to conclusively compare performance of improved vs baseline cooking methods, these results suggest that there are benefits for users of improved cookstoves.

Five charcoal stoves were also tested. All tested charcoal stoves performed better than improved wood fuel models and tripod baseline in terms of fuel consumption: the five charcoal stoves (which all performed similarly in terms of fuel use) consumed an average of 36 grams of charcoal per liter of water boiled. However, water boiling tests for charcoal stoves varied significantly, with the fastest stove averaging a boiling time of ∼14 minutes and the slowest exceeding 40 minutes.

Conclusion

This study provides a brief overview of the many interrelated impacts of traditional cooking practices in rural Madagascar. It is important to note, however, that this study focuses on a single village in the SAVA region, and results may not be generalizable to other regions or other countries in the world. Furthermore, these results are constrained by small sample sizes and further research is necessary to confirm the following conclusions.

Current cooking practices place huge demands on the local environment, which has a diminishing ability to meet those demands over time. Traditional cooking also poses serious health risks for women and children spending time in kitchens and requires substantial time for both head cooks and wood collectors. Improved wood stoves may add time to cooking, but have the potential to reduce consumption of wood fuels.

For the Duke Lemur Center and other NGOs operating in the region, there is an opportunity to promote education/awareness campaigns of the dangers of household air pollution and the benefits of using improved or clean cooking methods. There is also the opportunity to promote sustainable charcoal production, set improved cookstove design standards, and invest in cleaner burning fuels like liquefied petroleum gas while simultaneously promoting improved biomass stoves.

This study reveals that communities like Mandena are heavily reliant on biomass fuels for energy use, and price and access to markets constrains adoption of improved cooking technologies. Fuelwood collection places burdens both on the wood collectors and on the local environment. Cooking with fuelwood is a significant source of HAP, and poses serious threats to women and children's health. Despite the limited scope of improved cookstove markets, improved stove producers are thoughtful and creative. NGOs should work with local cookstove producers to develop and market improved stoves to reach those who stand to benefit the most from HAP and fuelwood reductions.

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