Development of Distributed Energy Resources for Large-Scale, Energetically Self-Sufficient Buildings

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***Abstract*—Major trends in Renewable Energy Technologies (RETs) innovation include incorporating Distributed Energy Resources (DERs); small-scale generators focused on private or comunal use instead of connection to the power grid. Examples of these include photovoltaic rooftops [e.x. Tesla] and panels aimed at achieving energetic self-sufficiency. Large-scale implementations of DERs could significantly reduce emissions reported from electricity production and industry sectors, and provide more economically viable power supplies to areas with low grid accessibility. Simultaneously, research endorsed by IEEE conducted in Khalifa & McGill University, highlights the potential of harnessing energy lost to human power in gymnasiums, while in their 2020 bulletin, Alzaareer and El-Bayeh describe the need to further develop high-efficiency RETs and storage systems. Lastly, there is humanitarian interest in developing energetically autonomous communities to empower citizens of areas with unreliable electric infrastructure or prohibiting tariffs. Therefore, this report studies the potential of harnessing kinetic energy to reduce Green House Gas [GHG] emissions attributed to building operations and mitigate energy poverty by conducting a three part study. First, the consumption profile of 229 building was analyzed to find that the average building electricity demand is majorly due to the draw from Heating Ventilation & Air Conditioning systems. Then, an exploration of the current technology human powered DERs indicated that the systems in the market generate sufficient power to meet certain building energy needs. Finally, a hardware development phase finalized a working prototype to harness energy generated during human exercise to power mobile devices. The compilation of these results implies that the large scale inclusion of these human powered systems requires a maximization of the power output and reduction of cost.**

***Index Terms*—Circuitry, Innovations, Controls, DC Microgrids, Tesla.**

I. INTRODUCTION

Energy poverty is defined by the WEF as an absence of “adequate, affordable, reliable, quality, safe and environmentally sound energy services to support development”. IEA’s World Energy Outlook estimates that 13% of the global population lacks access to electricity, primarily in Africa and South Asia; 40% of the global population resorts to solid biomass, coal or kerosene for their primary cooking fuel due to the unavailability of clean and sanitary alternatives. Along with the wide-spread health hazards of these dependencies, the lack of electricity supply for lighting, power and cooling directly impacts individuals’ opportunities to escape extreme poverty, particularly to be educated. The lack of a lighting infrastructure alone presents students with the conflict of using the daytime to study or contribute to the family’s financial stability, thus translating inlow graduation rates particularly in higher degrees of education. This subsequently increases the disempowerment of citizens.

With a 77% literacy rate, 80% of the population living in extreme poverty, 24% holding a university degree, 19%

[1] having access to electricity and 3% having access to clean cooking fuels, the Democratic Republic of Congo exemplifies the correlation between energy poverty and civilian disempowerment proven by M.A. Baloch (Baoji University, China). DRC is also home to the Congo Basin, the world's second largest rainforest after the Amazon, which over the past century, has lost 90% of its coverage to the expansion of the logging, mining, agricultural and livestock industries. According to With no qualifications for high-value jobs, civilians depend on these industries for financial survival - which is often found in industries or activities that contribute to the deforestation of the Basin, as well as working in conditions below UN's ethical labor standards. Energy poverty, low education rates, working conditions, civilian health and deforestation are thus coupled phenomena.

This is the motivation for research on alternative renewable energy resources capable of satisfying full building electricity demands. As a first step in the solution of this problem, the research conducted this summer, and subsequently this report, aims to open the needed exploration along different fronts. Particularly, the report will cover three spheres: building energy needs - to understand how much electricity is needed to maintain carbon neutral buildings -, current technology and underlying physics - to determine what components and techniques could maximize power output with low budgets -, and hardware development - to test the theoretical conclusions and identify practical concerns. To present the progress made this summer, the report will first expose the materials and methods employed, subsequently presenting the results and finally discussing their interpretation as well as suggesting further research topics and improvements.

II. MATERIALS AND METHODS

A. Characterization of Building Energy Profiles Across New York State

This phase was carried out throughout the month of June, with the objective of deriving the electricity consumption needs of buildings in different industries and categories throughout New York State localities. To do so, the research used data from 229 buildings along 11 categories in 68 locations published in NYSERDA's Real Time Energy Hackathon. Figure 1, for example, illustrates the geographical distribution of the sample, demonstrating the variety in site conditions and a majority in urban localities, primarily New York City. Figure 2, on the other hand, represents the spread in building categories, indicating a majority in the multi family sector, followed by commercial retail and office spaces.

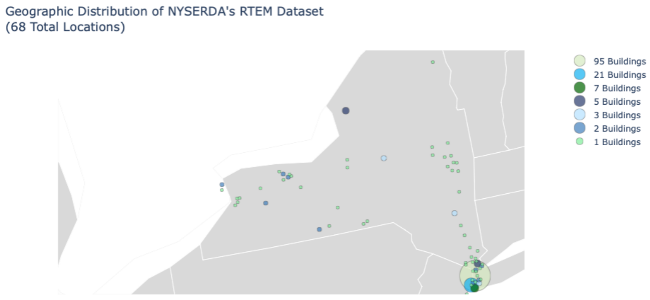

Fig. 1: Geographical Distribution of Dataset

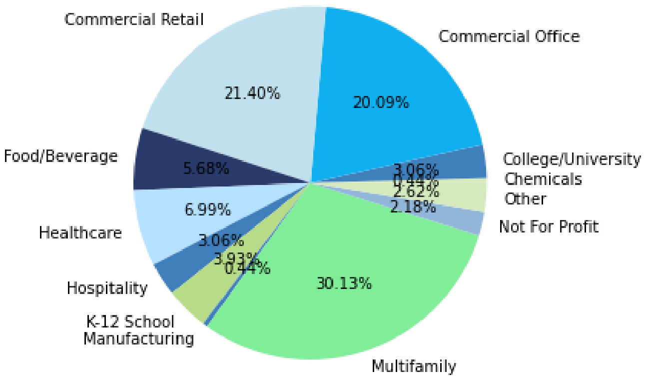

Fig. 2: Representation of 11 Building Categories in Dataset

Besides providing an array of locations, NYSERDA's

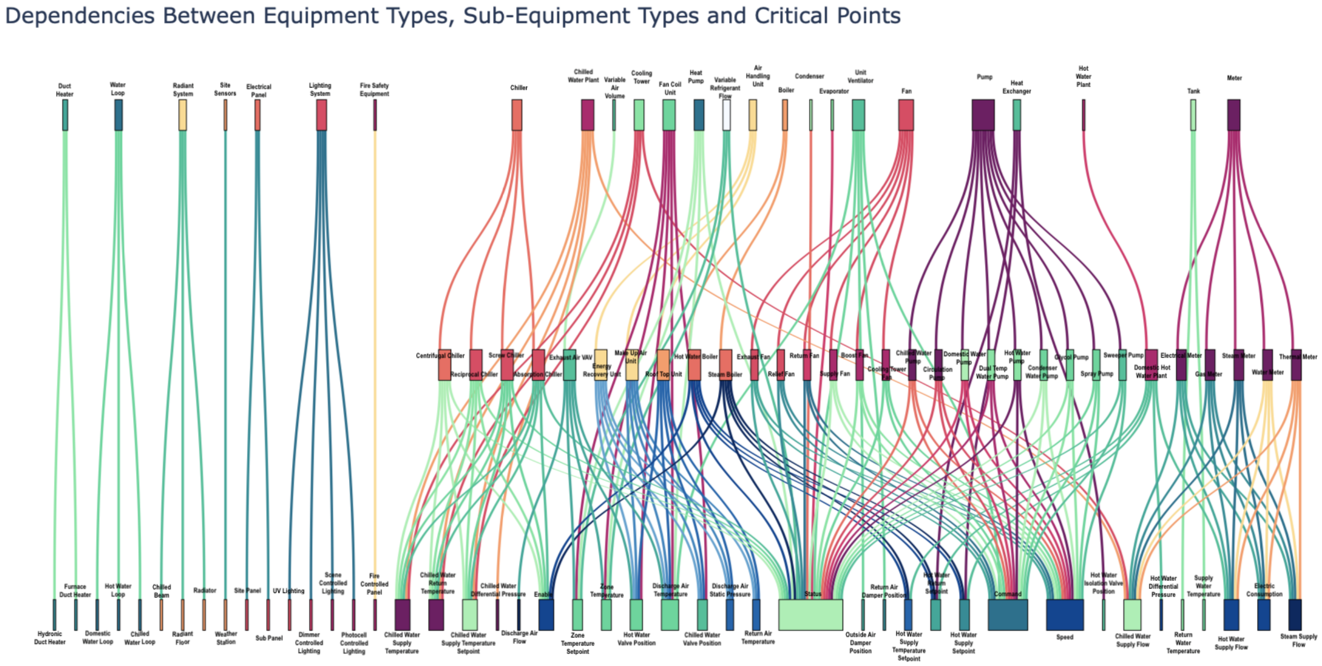

Fig. 3: Equipment Types (Top) Associated with Subequipment Types (Middle) and Point (Bottom) Dependencies

database included detailed information surrounding building controls. Prior to releasing the database, the public entity aggregated third-party installed meter systems. These devices, which were split into real time and static measurements, quantified the physical conditions surrounding building operations, from Heating Ventilation and Air Conditioning (HVAC), to occupancy sensors. In the database's terminology, they were referred to as ”points”. Points were also linked to equipment types for each operation, which relied on sub-equipment for more specific applications. These were monitored through ”point” meters. Figure 3, for example, demonstrates the complexity in dependencies among the 183 data structures compromised by equipments, subequipments, and points. The analysis structure was the following:

1) Data Acquisition & Cleansing:

   The information was extracted from NYSERDA's Application Programming Interface (API) and outliers were detected.

2) Data Modeling & Exploration:

   The equipment and energy consumption distribution was calculated for the buildings that had functional electricity meters.

3) Visualization & Presentation:

   Figures were designed to explain the process and results.

The analysis and data visualization methodologies were automated through Python to allow the future inclusion of external databases. This process in itself employed additional libraries and datasets. Special emphasis was placed on visualizing each building's characteristics, both regarding equipment distribution and energy consumption. Finally, secondary sources were explored to confirm the results of the investigation.

B. *Exploration of Technologies and Underlying Physics*

This phase, which was carried out mainly in the first two weeks and a half of July, and intermittently until August 10th, prioritized determining the mechanisms, flaws and features - within the power demand and financial constraints - of the following:

1) Pre-existing Technology that Harnesses Human-Generated Kinetic Energy
   Initially, it was necessary to understand the presence and history of human-powered generators in the market. Doing so required parsing patent and company databases as well as public sites such as Youtube, GitHub and Engineers For a Sustainable World's project repository.
2) Power Storage, Inverters & Distribution Systems:
   First, a general study was conducted to find the marketed product that best suited the technology constraints: power output and cost. This study covered technologies from the grid level (i.e. inverter, wire types and materials) to the device charger level (i.e. determining whether wall chargers or car chargers best met the design constraints). Later, a patent search was conducted to find inverter and storage technologies that minimized losses at the lowest cost.
3) Motors & Generators:
   Due to the scope of the research, the purpose of this section was to identify the physical principles and techniques behind the design of motors and the difference between using motors for regenerative braking versus manufacturing generators. Moreover, the literature review also aimed to distinguish different kinds of motors to find the technology with highest power output at the lowest price.

C. Hardware Development

This section of the research spanned the last two weeks of July and the first week of August. Its aim was to develop a prototype of an improved version of current, human-powered generator. The design procedure began with calculations, and finalized with a prototype. Table 1 in Apendix A portrays The Bill of Materials.

Furthermore, the prototype was itself divided into three systems: the power generation, transmission and consumption mechanisms.

The power generation mechanism was constructed applying regenerative braking principles to a brushless DC motor. Unlike brushed motors, brushless motors have an external stator - where wires are winded around an iron core - and an internal rotor - formed by a rotatable permanent magnet, eliminating the power losses due to the friction of the rotating commutator in a brushed motor. Specifically, the prototype used RC motors for their market availability, customizability and cost-effectiveness. The most relevant calculation surrounding the power generation mechanism determined the KV rating of the motor so that average pedaling speeds will yield 9-15V. To do so, the following measurements had to be determined:

- $\mathcal{C}_{tire}$: the circumference of the tire, measured with a ±0.005m uncertainty.
- $\mathcal{C}_{dw}$: the circumference of the drive wheel shaft, measured with a ±0.0001m caliper.
- $\mathcal{R} = \frac{\mathcal{C}_{tire}}{\mathcal{C}_{dw}}$: the wheel ratio, or amount of times the drive wheel will rotate per rotation of the tire.
- $\mathcal{V}_{av}$: the average human riding pace of 15MPH.
  times
- $\mathcal{V}_{av}$: the average human riding pace of 15MPH.

For the materials used, $\mathcal{C}_{tire}$ = 1910mm, and $\mathcal{C}_{dw}$ = 30mm, which yielded $\mathcal{R} = \frac{1910}{30}$ = 63.67. At $\mathcal{V}_{av}$, the tire rotated at:

$$\omega_{tire} = \frac{15mi}{1h} * \frac{1h}{60min} * \frac{1609344mm}{1mi} = \frac{402336mm}{1min}$$
$$= \frac{402336mm}{1min} * \frac{1rev}{1910mm} = \frac{210rev}{1min} = 210rpm$$

Therefore, the drive wheel rotated at:

$$\omega_{dw} = \mathcal{R} * \omega_{tire} = 210rpm * 63.67 = 13370rpm$$

Which implied that, for a user to generate 12V at $\mathcal{V}_{av}$, the motor's KV rating should be:

$$\mathcal{KV} = \frac{\omega_{dw}}{12V} = \frac{13370rpm}{12V} \approx 1114$$

Reducing the KV rating results in an generating 1V with less effort from the user, therefore the prototype was implemented with a 920KV RC motor, specifically for drone applications - as these were more available and had lower cost. The shaft from this motor fit directly in the bicycle trainer shaft as demonstrated in Figure 4:

Fig. 4: Brushless DC, RC Motor Connected to the Bicycle Trainer for Power Generation

Since a three phase DC brushless motor was used, the power transmission mechanism involved a 3-phase rectifier. To monitor the power generation, I also attached a power-meter. Upon testing, the purchased meter resulted to be faulty, and time constraints eliminated the possibility of requesting a new one. Subsequently, voltage and current generation were monitored through oscilloscopes. This also prompted the use of Arduinos as power controls, and wifi modules were purchased to transmit information through TCP protocols for monitoring from computers. The implementation of this concept was not fulfilled by the end of the research, and will be a first topic of interest in the development of future modules.

Average mobile devices are charged at 5V, meaning that in the junction between transmission and device power consumption the need to insert a power converter arose. As an initial trial, the prototype aimed to direct current through a boost/buck converter that would output 12V whether the input voltages were above or below 12V. Next, a 12V socket would open 3 parallel lines onto which 5V car chargers were placed to power devices - which closed the circuit on the power device consumption end.

III. RESULTS

A. *Characterization of Building Energy Profiles Across New York State*

The conducted literature review suggested that regular office spaces distribute their demand as indicated in Figure 5, with HVAC systems ranking highest, particularly fans, followed by lighting and office equipment.

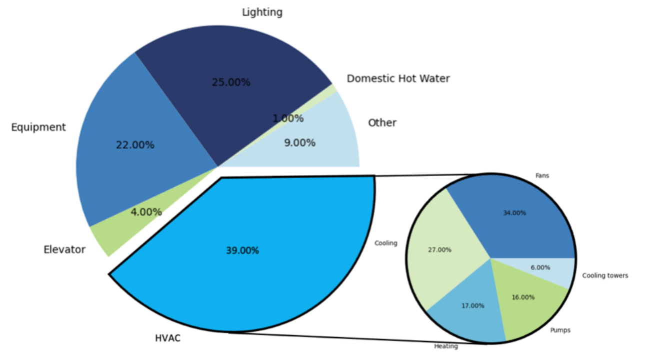

Fig. 5: Distribution of Building Electricity Demand per Equipment Type

On the other hand, information provided by NYSERDA's database was insufficient to produce a reliable ranking of power consumption per equipment type. Although trends suggested that HVAC systems were also featured highest, the lack of functional meters and uneven distribution of equipment representation impeded obtaining an average consumption per equipment type and consumption ranking, specially among sub equipments. To solve this issue, an additional literature review followed the data analysis, determining that HVAC systems a) had a demand dependant on the sub equipment types used,

b) aimed to fulfill functionalities that could be satisfied by heat pumps at minimum demand. Therefore, the average yearly consumption for heat pumps was estimated to be 331kWh/year [8], meaning that heat pumps operated at 37kWh.

B. *Exploration of Technologies and Underlying Physics*

1) Pre-existing Technology that Harnesses Human-Generated Kinetic Energy

   Findings to the first phase differentiated between open source and private efforts. On the private side, companies such as Energy Gym, ReRev and The Green Microgym, have released human powered generators to the market. Out of the three, the former is a startup with the most innovative technology. Their aim is not to power devices directly but rather to generate electricity that can be stored in portable batteries. Whereas their patents were not found, ReRev's technology was indeed found. Additionally, a study conducted by Maha Haji, PhD from MIT and Assistant Professor at Cornell University, examined the implementation of ReRev's technology in a college campus gym, providing perspective about the power supply and building electricity demand. Technology discovered from open source projects provided cost-effective methods to achieve relatively high power yields. The hardware developed in this study followed the recommendations of Source [9].

2) Power Storage, Inverters & Distribution Systems:

   It was found that car chargers had greater efficiencies, and that stranded wire should be used for networks needing wire flexibility. Then, power losses and cost for both energy storage and inverters seemed to be minimized in Tesla's devices. Tesla's devices were also attractive because of the benefits provided by the company's publicity, influence on the market and recent humanitarian donations. Moreover, research conducted on optimal transmission networks indicated that low voltage DC microgrids could meet safety, budget and efficiency constraints.

3) Motors & Generators:

   Given the advantages of Tesla technologies in the framework of these constraints, their patents were also reviewed to find cost effective generating techniques. Their regenerative braking principles indicated that using motors as generators would be fitting. Therefore, and as discussed in the methodology section, brushless DC motors, specifically those designed for RC applications, were found to be the most cost effective devices with the highest output. Hanselman's Brushless Permanent Motor Design was a pivotal resource in the understanding the difference between brushed and brushless motors, as well as AC and DC motors to determine these results.

C. *Hardware Development*

The developed system generated an average of 20V, with a minimum of 2V - when the bicycle pedal was steered by hand, and a maximum of 51V when the bicycle gears were arranged to provide highest resistance. The output testing this set up, was greater than the boost/buck converter could process, which damaged the circuitry. This compromised the development of the prototype, and an arrangement of a 9-39V to 12V boost/buck converter along with an adjustable 3.7-34V boost converter that was set to 9V, replaced the previous converter. Due to the faulty power meter, no power output was confirmed, yet theoretical calculations suggest that an individual bicycle generator could supply 100-400W.

IV. DISCUSSION

The results derived through this methodology met the desired expectations. The hereby section aims to review these findings and provide criticism in the research development, as well as identify future topics of interest.

A. Characterization of Building Energy Profiles Across New York State

The results revealed that HVAC systems consumed the most out of all the equipment types associated with building operation. These results were within expected ranges, as suggested by the literature review.

A point of improvement for future work would be to ensure that the same meters are functional across all buildings in the database. Whereas the installed measuring devices enabled determining that HVAC systems consumed most electricity, not enough buildings provided HVAC sub-equipment data - e.g. Fan Coil Units (FCUs), fans, Air Handling Units (AHUs) - to determine the specific energy demand of different applications, develop a consumption hierarchy, and identify which systems can be powered by human kinetic energy. Figures 6.a, 6.b and 6.c, for example, illustrate that the equipment count of buildings often provided more information about HVAC equipment than others, which could compromise the validity of the findings. This was not always the case, as instantiated by Figure 6.d, but does indicate that deriving reliable conclusions requires having equal information of all devices in a building. Even more important, however, is the need to develop databases with reliable electricity meter information in available in the API. In NYSERDA's database, electricity consumption information was available through specific meters whose associated measurement unit was ”kJ” or ”kWh”. Although varied, the database did not ensure that all subequipments had a retrievable energy meter, which resulted in the unreliable results discussed earlier. Finally, a relevant addition to this research could be to compare the demand of computer equipment to that of HVAC. As the distribution in Figure 5 already indicates that after HVAC, consumption due to office equipment is also high.

B. Exploration of Technologies and Underlying Physics

1) Pre-existing Technology that Harnesses Human-Generated Kinetic Energy
   Having found attempts to commercialize human-powered generators, and determining that it is not mainstream technology, indicates that there is a reason why the large scale implementation of these technologies has not yet occurred. Future work should delve into the reasons why past technology has not been successful in order to prevent future mistakes and learn from those of previous designs.

2) Power Storage, Inverters & Distribution Systems:
   Finding a nexus between cost effectiveness and power output in a company such as Tesla prompts for a further development of the possibilities of using their technologies as components in a larger system. Thus far, the study has considered self sufficient systems without grid access. However, the large scale application of human-powered generators will require developing grid-like interactions, potentially in the form of low-voltage DC microgrids, as indicated by the findings. Tesla components do not operate ideally in these environments, which calls for an iteration of the literature review with this new context. Moreover, since technology changes rapidly and is abundant, it is crucial to recognize that as thorough as the patent search could be, there may still be either emerging or existing technology that is more fitting to the constraints.

3) Motors & Generators:
   Before conducting the literature review, there were expectations that manufacturing a generator specific for harnessing kinetic energy from exercise would maximize

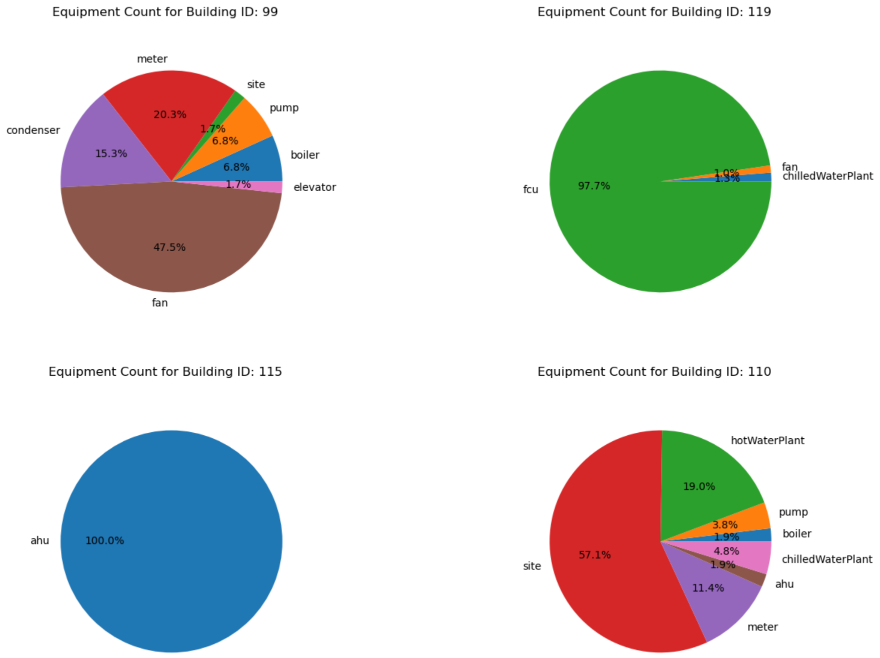

Fig. 6: Equipment Count for Buildings (a) 99 (b) 119 (c) 115 (d) 110

> power output. The study confirmed this hypothesis, yet the cost of said systems would be beyond the plausible constraints. Therefore, it was determined that the currently marketed technologies capable of generating most power within low budgets, for this prototype, were brushless DC RC motors. In the development of future prototype iterations, these conclusions could be reassessed, since attempts to design low cost, efficient generators specific for the angular speeds determined in the hardware development stage could improve the model.

Further criticism of the literature review could be directed towards the methodology. Section 1: *Materials & Mechanisms*, outlined the three sub sections that compounded this literature review. The combination of both, market research and physical understanding of general technology provided a solid foundation for this research. However, a deeper study of the differences between more successful devices can enable adopting succesful techniques to improve performance. Moreover, future work should further explore the physics behind current successful technologies given the cost and power output constraints. Furthermore, throughout this report, the power consumption trends have been assumed to be similar to electricity consumption trends, and both demand tendencies have been used interchangeably. However, future work should determine whether the goal for self-sufficient buildings is to focus on maximizing power or energy.

C. *Hardware Development*

The voltage outputs for the individual device were within the expected ranges. However, these results are very reliant on the dimensions of the bicycle used. Future work should explore different tire to wheel ratios. The bicycle gear chosen also altered the voltage output, which indicates that this should also be considered to maximize power.

Future improvement of the prototype should furthermore include an optimization of human pedaling rhythms, potentially including Maximum Point Power Transfer technologies. Moreover, the next iterations of the generator's power transmission networks should make use of the findings in Section 2, specially those that compromise the power output through losses, as is the case of the inverters. Tesla's technology particularly optimized the constraints given by energy poverty in Democratic Republic of Congo and their application should be further explored. More specific to the development process, next iterations should begin the research by determining and ordering the parts needed before conducting theoretical research. This will ensure that the parts have arrived by the opening of the hardware development phase, avoiding time loss and providing flexibility for erroneous shipments, part shortages, etc. Additionally, ordered components should be in sets of two: always ensuring that there is one extra in case one came faulty or was broken in the development process. With regards to the components, the hardware development was a success: the prototype expenses were much less than expected, indicating that even with unexpected occurrences, the manufacturing procedure was efficient.

On the other hand, the obtained power output was within the bounds of heat pump needs derived in Section 1. Therefore, another topic of exploration would be to expand supply - consumption network from one bicycle generator - one load scenario, to multiple generators and multiple loads. Finally, to maximize the effectiveness of this work, future progress should include the stochastic analysis of controls, loads and generation cycles.

V. CONCLUSION

In conclusion, this report first presented the motivation behind developing alternative renewable energy technologies that satisfy full building electricity consumption demands: increase access to reliable electricity. Additionally, the introduction linked energy poverty to environmental and humanitarian concerns such as deforestation and extreme poverty. The research proposed sought to cover three aspects: determine common building energy demands, review literature on pre-existing technology and physical concepts, and finally develop the hardware needed to test the theoretical findings and identify potential next steps. The report first covered the materials and methodologies of each research section, then exposed the results and finally discussed, interpreted and critiqued both results and methodologies, while also suggesting future areas of interest. This research has finalized with a working prototype of a human powered generator using a brushless DC, RC motor, a boost/buck converter system and a 12V transmission line that can charge up to 3 mobile devices. Given the compiled information, the continuation of this research should involve the inclusion of two human powered generators, in order to determine the network dynamics between generators. Then, multiple loads can be included, and then connections to the grid can be devised. Once the network mechanism has been established, the device should be redesigned to optimize power output, minimize losses and reduce cost in order to meet the constraint given by the desired application: electrifying aisolated villages in developing countries, specifically in DRC.

Appendix A

Bill of Materials

Item	Provider	Cost	Qty.
340KV RC motor	Mad Components	$64.00	1
RC motor	Joseph Skovira, Cornell ECE	N/A	1
Bicycle Trainer with Magnetic Resistance	Balance Form	$46.39	1
100A, 1200V 3 Phase Bridge Rectifier	Amazon	$12.19	1
RC Power analyzer meter or Drok meter	Amazon	$15.99	1
12v Socket Outlet	Amazon	$10.59	1
12v Socket Outlet with Switch	Amazon	$17.97	1
Power Inverter	Bovay Laboratory Complex	N/A	2
Spade Connectors	Hollister Hall Machine Shop	N/A	5
XT60 wire assemblies	Cornell Engineering Maker Space	N/A	2
39w Car Charger	Anker	$15.99	1
40w Car Charger	Anker	$23.99	4
Bicycle	Old Goat Gear Exchange	$285.00	1
Arduino MKR WIFI 1000	Arduino	$90.93	2
Arduino MKR WIFI 1000	Digikey	$285.00	1
Shaft Coupler	CEE Machine Shop	$100.00	1
LCD Display	Joseph Skovira, Cornell ECE	N/A	1
Boost/Buck 5V Power Converter	Joseph Skovira, Cornell ECE	$14.67	1

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