Final Report: Speed bump

Adam Johnson, Andrew Rasetti, Avery Taylor, Gabe Debs, Tina Machado, Grace Llewellyn

Advised by: Dr. Emily Klein, Dr. Eric Rohlfing, Dr. Josiah Knight

Bass Connections 2021-2022

Executive Summary **1**

Introduction **1**

Description of Approach **1**

Analysis **2**

Technical Design **2**

Evaluation and Results **3**

Environmental Benefit Analysis **5**

Social Benefit Analysis **5**

Target Market **6**

Budget **6**

Basic Business Plan **6**

Government Incentives **9**

Conclusion **10**

References **12**

Appendix **13**

Executive Summary

Throughout this year, our team has worked to design and create a device that is able to convert the mechanical energy exerted by a vehicle into electrical energy. We did this by prototyping a system that utilizes the basic functions of a speed bump for the purpose of energy capture. We considered multiple different approaches to design this project and evaluated these choices with a design matrix. We evaluated both the quantitative and qualitative environmental and social benefits that might be achieved upon implementation of scaled-up versions of the proposed speed-bump prototype to evaluate the efficacy and practical impact of our project. Energy storage calculations revealed a potential for 0.04kWh of storage in our prototype system and1.35kWh of storage for a scaled-up model. We didn't get to the stage of this project generating electricity, but we recommend it for future groups. We considered multiple ideas for this project, and our final design utilizes an air cylinder to supply outside air into a compressed air storage tank. There are many sources of wasted energy in our environment, and this project is working to harness some of that wasted energy. Throughout this report, we detail the motivation for our project, the technical design, some benefits of our project and a theoretical business plan.

Introduction

One of the most important energy challenges facing our world today is the conservation of energy, and moreover the generation of clean energy. We noticed that there were many common instances of energy production that were not being utilized. Our project then became creating a system that could harness waste mechanical energy that was otherwise left unused. Once we identified this common goal, we decided to create a design that would harness waste mechanical energy from a speed bump.

Because speed bumps already exist for public safety, we believe that this project can be used without changing the function of the speed bump, therefore emphasizing its scalability. Moreover, our goal was to implement our prototype onto Duke's campus, and use the energy generated from our device to power a Blue Light, which is used for safety around Duke's campus.

Description of Approach

We first approached this project by looking at similar projects that had been done in the past. From these examples, we looked at what had been done well and what had failed. Overall, we could not find many examples of this speed bump project, so we decided to attempt it. We first made a list of different designs that we could attempt. These design ideas are shown in Figure 1 in the appendix and were: hydraulic, compressed gasses: open loop (air), compressed gasses: closed loop (other gasses), piezoelectric, combination piezoelectric and hydraulic, and mechanical (axel and generator). We weighted these different ideas in a decision matrix on the criteria of: cost, technical complexity, power output/ capacity/ efficiency, safety, environmental impact, and maintenance. Each of these factors had different weights and we assigned each project idea a 1-5 rating for each factor. Both the compressed gasses: open loop and mechanical (axel and generator) tied for the winner with 4.1 total points. To break this tie, we voted as a team which project we would rather do. We decided on the compressed gasses: open loop approach using air as our gas.

Next, we began designing the project. When designing the project, we collaborated with the professors to create a design that would work mechanically. Since none of us are mechanical engineers, we struggled slightly in this aspect of the project, but also learned a lot as well. We quickly realized that we would probably need a compressed air tank. From that tank, we would need a turbine to spin from the released air and that would spin a generator that would generate electricity. We first focused on getting the compressed air into the tank. Our final design was using a pump to get the air into the tank. From there, we worked out a technical design with fittings that would allow air to go into the pump to be pumped into the tank. In the end, we realized that generating electricity was out of the scope of this capstone, but the final implementation should include this feature.

Analysis

We chose our final design with the help of the professors. We came to them with various ideas, and with their expertise, they helped us select a final design. We also explained the choice of this design in the description of the approach section.

After we selected a design, we began to order our parts on McMaster-Carr. We started with a compressed air tank that Dr. Knight gave to us from a past group. We worked using this compressed air tank into our design because it saved our budget a lot of money. This meant that all the fittings needed to be able to connect to the input of the compressed air tank. For the parts we needed with their specific sizing, there wasn't a huge range of selection on McMaster. The main part we needed with variability was the pump. We ultimately decided to get the second largest pump to increase our output. The pump ended up being larger than we expected it to be, but we still incorporated it into our design. We also chose a pump with a universal mount that would make it easier to do a hinging mechanism that allows us to put the pump sideways (which was a consideration we had before realizing how large the pump was when we got it).

We chose to use check valves because it was the simplest way to prevent air from going back into the tank and back out to the air input source. We used a tee connector to accomplish the 3-way connection of the pump, tank and input air. The tubing we chose was rated to support air well. We decided to use McMaster for these purchases because it had a large range of selection and quick shipping.

Technical Design

As seen in Figure 2 in the appendix, our design includes an air cylinder, a T-valve, 2 check valves, tubing, and a 7 gallon air tank. Not pictured in this schematic are the threaded pipe fittings, hose clamps, and Teflon tape that we used in order to secure a tight fitting and minimal air leakage. The air cylinder, T-valve, check valves, tubing, hose clamps and threaded pipe fitting were purchased from McMaster-Carr, while the 7 gallon tank and the Teflon tape were found in the lab and adapted for our use in the interests of time and cost. Table 1 in the appendix also shows the specifications of these components.

Next, Figure 3 shows the rudimentary pumping mechanism that we created with the help of Dr. Knight. When the junction between the two pieces of wood is pushed down, it exemplifies the process of a speed bump as a car drives over it. This pumping mechanism is attached at full extension of the pump and the bungee cords act as a spring, which builds tension so that the mechanism resets after being compressed.

When the mechanism in Figure 3 is executed, the piston of the air cylinder is pumped (as seen in the black arrows in Figure 2), and compresses the air. This compressed air then flows through the tubing, t-valve, and check valve into the tank, where it is stored. The function of the t-valve and check valves is to make sure that compressed air only flows into the tank, and outside (uncompressed) air flows into the cylinder (where it will be compressed). Specifically, the check valve pointing towards the tubing intakes outside air that is transferred to the air cylinder, while the check valve facing the tank makes sure that compressed air does not come back into the system once it is in the tank.

At the current state of our technical design, the final step is storing the compressed air. Although, we would want to attach the 7 gallon tank of compressed air to a turbine and generator, which would then generate electricity.

It is very important to note that this prototype is being used to demonstrate concept, not as a final design. This is a small-scale system for testing only, not the system that could be used in a real application. Specifically, the air cylinder is not necessarily suitable for the application of a speed bump because it does not naturally retract after compression, and is very large. Furthermore, the pumping mechanism is made out of wood, which would not be able to withhold the weight of a car. Finally, the speed bump itself could not be this high, as it would create safety problems.

Evaluation and Results

Testing consisted of manually compressing the air cylinder to pump air into the tank and quantifying the energy stored. We took note of the number of compressions necessary to reach a certain pressure, which is an approximation for the number of cars it would take to fill the tank of a full-scale model. Data collected during testing is summarized in a plot of tank pressure as a function of the number of compressions:

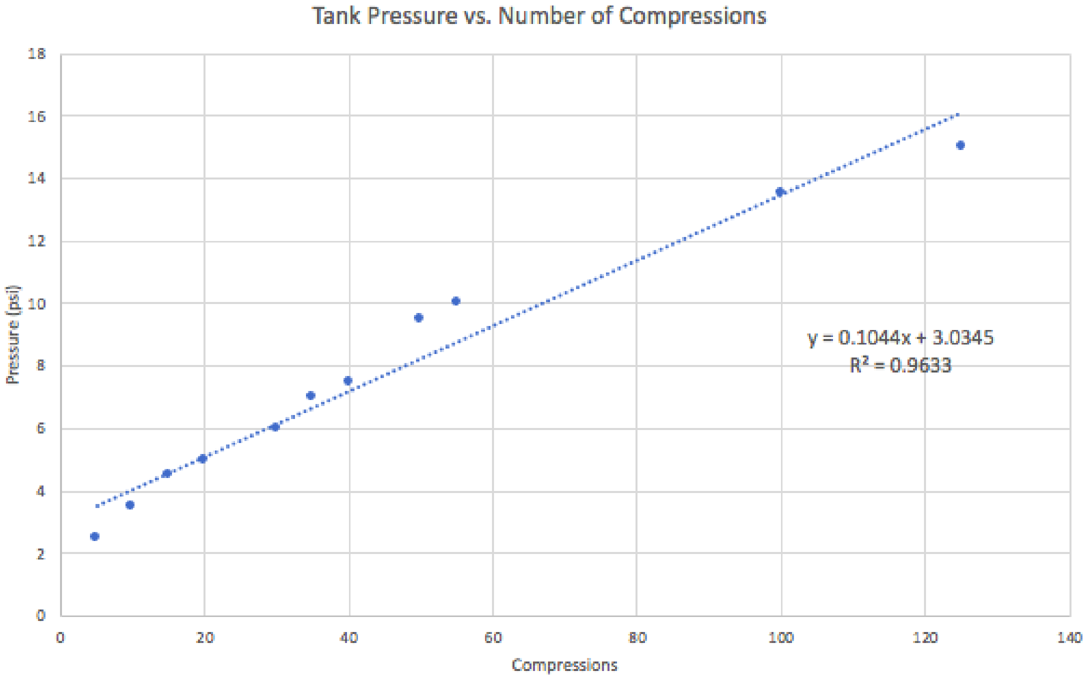


Figure 4: Tank Pressure vs. Number of Compressions

Using the line of best fit equation, the number of compressions needed to fill the prototype tank to its full capacity of 160 psi was calculated to be 1529. To estimate the energy stored in the full prototype tank, a derivation of the work required to pressurize ambient air into the tank was used. The equation is as follows:

$$W = -C \int_{V_o}^{V} \frac{dV}{V} = -C \ln\left(\frac{V}{V_o}\right)$$

The work necessary to fill the prototype tank, and therefore an approximation of the work of expansion when the air is released, was calculated to be 0.04 kWh. The large number of compressions necessary to achieve this small amount of storage underscores the inefficiency of a system at such a small scale. To approximate the energy stored in a system of a more realistic size, the same equation was followed using the measurements of a theoretical 100 gallon tank with a maximum capacity of 500 psi. The work necessary to fill this tank was calculated to be 1.35 kWh. The number of compressions necessary to reach capacity would be much higher than the approximation calculated for the prototype tank, given that it would be difficult to scale up the size of the pump and still contain it in a reasonably-sized speed bump. Again, the amount of energy stored in this system is not particularly impressive considering the number of compressions needed; a 500 gallon tank with a 2000 psi maximum capacity could store a more meaningful amount of energy (39 kWh), enough to power a single family home for about a day. Therefore, having a larger pump is something we considered. In order to successfully create a speed bump with a pump our size, and even a bigger pump, we needed to create a linkage mechanism so that the pump could be sideways.

While the above calculations indicate that scaling up the volume and pressure capacity of the tank would allow for larger amounts of energy to be stored and generated by the speed bump, larger size tanks, using the same size pump as used in our prototype, would likely be unfeasible to implement due to the sheer number of compressions required to adequately pressurize them. With the assistance of Dr. Knight, a series of calculations surrounding the physical mechanics of the pump were completed to develop a relationship between force generated by the piston of the air cylinder of the device (F_P), the weight of the car passing over the bump (W), and the degree of compression of the speed bump (indicated by the angle of elevation between the ground and the speed bump pumping mechanism (α). The derived relationship was $F_P = \frac{cos(\alpha)}{sin(\alpha)}W$, and the weight of the car passing over the bump was assumed to be a nominal fraction of a car's weight at 500 lbs. The force generated by the piston was plotted over a range of linkage extension angles (See Figure 5), and it was determined that, as the degree of compression of the bump decreases, the force generated by the piston decreases significantly beyond α=10-20°. This is not an issue, considering the typical feasible extension of the linkage is approximately α=10° for typically sized vehicles passing over the bump.

Thus, at α=10°, the force generated by the piston after 500 lbs is applied to the bump is approximately 2835.64 lbs. In order to achieve a desired pressure for compressions at α=10° of, for example, 200 psi, then, the radius of the pump piston would need to be approximately 2.12 inches (See calculation in Appendix B). For a pump with such a piston, and a pump stroke length of 12 inches like our prototype, the volume of air added to the tank per compression of a single piston would be 2.78 L. Using Boyle's Law and manipulating the ideal gas law for pressure and volume of the piston and tank, it was calculated that this addition of volume results in an increase in the pressure of the tank of approximately 0.219 psi/compression. Thus, for a scaled-up prototype, with larger piston radius and 10 pistons acting to pressurize air simultaneously as vehicles pass over the bump, the number of compressions required to fully pressurize a 50 gallon tank with a pressure rating of 200 psi is approximately 92 compressions of the speed bump (See Appendix B). While such a pump with such a large piston might not be completely feasible in the context of implementation as part of a small speed bump, piston radius could easily be further decreased to obtain larger piston pressures. These calculations prove the feasibility of full-scale implementation of the waste-to-energy speed bump at the size of a real speed bump and for load-bearing of full-sized vehicles. The only design improvements required to achieve this full-scale implementation are in regards to pump and piston scaling, and optimal speed bump linkage design to ensure compression of 10° or greater for each vehicle that passes over.

Environmental Benefit Analysis

This waste-to-energy speed bump prototype was designed to reduce additional emissions associated with the production of energy for powering roadside devices, such as campus Blue Light safety features, or traffic cameras, as well as reduce energy consumption on college campuses more generally. As vehicles in high traffic areas pass over the waste-to-energy speed bump, the depression of the speed bump piston converts otherwise wasted mechanical energy into pressurized air, which can be stored and utilized for energy production. This generated energy contributes to an excess of energy production on campus, and can be used to generate power for roadside devices, reducing their reliance on the campus power grid.

In order to quantify the emissions offsets achieved by the waste-to-energy speed bump, during testing of the prototype, the theoretical amount of kWh produced per compression of the piston will be quantified and compared to the maximum theoretical amount able to be produced given the limitations and constraints of the prototype's design. The kWh of energy produced during testing can then be extrapolated to determine the kWh of energy likely produced per speed bump per vehicle were the prototype implemented at full scale on a college campus. Using this value for the energy generated, the emissions offset can be calculated by drawing on energy production data for the college campus on which the speed bumps are implemented. The mix of fuel sources and energy production methods which converge to supply power to the campus energy grid, and the associated amounts of each fuel source required to produce a certain amount of kWh of energy and/or amount of greenhouse gas emissions can then be used to firmly quantify the emissions offset, cost savings, and general fuel savings facilitated by the implementation of the waste-to-energy speed bump prototype.

The theoretical maximum amount of energy able to be stored in the example tank (500 PSI and 100 gallon volume) would amount to 1.35 kWh. Accounting for losses due to the efficiency of the piston, turbine, and energy interconversion, approximately 0.675 kWh of this theoretical energy would be able to be practically harnessed. Assuming that Duke pays the average retail electricity price (2020) for North Carolina at 9.43 cents/kWh (EIA), that there are 100 of these waste-to-energy speed bumps implemented on campus, and that each speed bump tank is filled completely over the course of one day, on average, through the use of a scaled up pump than that of our prototype, the energy produced by these speed bumps would save Duke approximately 6.36 $/day. Similarly, assuming that Duke produces emissions at the national average rate of 0.85 lbs of CO_2 per kWh of energy produced (EIA), then, for 100 waste-to-energy speed bumps each producing 0.675 kWh per day, the speed bumps produce a theoretical carbon emissions reduction of approximately 57.375 pounds of CO_2 per day.

Social Benefit Analysis

Compared to the environmental and economic benefits produced by the waste-to-energy speed bump, the social benefits of such a device are far more difficult to concretely quantify. Non-quantitative social benefits can be assessed via surveys of the community where the speed bumps are installed, pedestrian and driver satisfaction metrics, and analysis of traffic safety data. The implementation of a speed bump which reduces and offsets the negative environmental impacts of driving greenhouse gas emitting vehicles while simultaneously providing additional power for vital roadside pedestrian safety features, such as campus Blue Lights. These features coalesce to produce a plethora of positive social benefits, including more conscientious, slower driving in high traffic areas, increased safety on campus, both for vehicles and for individuals, an increased awareness of environmental issues among community members, and a sense of empowerment in them for the ability of individuals and institutions to take action to combat the climate crisis. All these non-quantitative benefits can be assessed periodically, over the course of the waste-to-energy speed bump's lifetime via random surveys of community members who interact with the speed bumps.

Target Market

The primary users of this waste-to-energy speed bump prototype are any and all vehicle operators that drive on high-traffic campus roads. Due to the indiscriminate, non-specific users for a speed bump technology, in-depth analysis of the consumers of such a technology is far more constructive for a detailed market analysis of the prototype.

The primary consumers, then, of this technology are the colleges and universities which will implement waste-to-energy speed bump(s) on their campuses and allow for usage of the energy they produce to offset their emissions. Thus, when marketing the waste-to-energy speed bump prototype, the target market of college campus administrations should be considered, with marketing focused on the reductions in energy usage, emissions, and costs that the product provides, while simultaneously improving campus safety and student satisfaction. With the current push on my college campuses, both across the United States and throughout the world, to increase energy efficiency, cut emissions, and become carbon neutral, there is no better time to market a waste-to-energy speed bump prototype with strong potential to augment a college's carbon offset efforts. At Duke University, in particular, the push for carbon neutrality by 2024 is heavily driven by focusing on carbon offset efforts, and waste-to-energy speed bumps would be a cost-effective method of achieving increased offsets directly on campus, harnessing the normal movement of vehicles that would occur regardless.

Budget

Our budget breakdown is shown below in Table 2. Total we spent $320.74.

Part	Cost
Pump	$116.82
Tee connectors	$46.26
Check valves	$53.70
Teflon Tape	$14.53
Barbed hose fittings	$67.32
Plastic tubing	$13.40
Worm-drive clamps	$8.71

Table 2: Parts and their costs

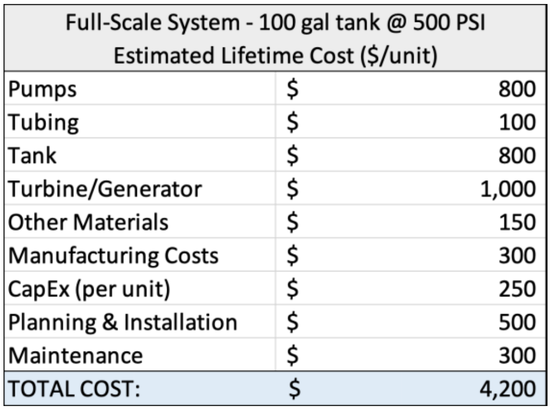
Basic Business Plan

The market prospects for waste-to-energy speed bumps of this kind are generally limited, but a scaled version of our group's prototype does have the potential to be economically viable. We assume that the number of pumps in the speed bump could be significantly increased to scale the overall system's output compared to our prototype, but there is still a challenge in economically capturing sufficient electricity to offset the costs for a full-scale system. Moreover, conventional speed bumps are inexpensive and have long operational lifespans, so the relatively high costs of an energy-capture system comparable to our prototype would make initial market penetration a challenge. Nonetheless, estimates of the revenue, costs, and payback period for a full-0scale system are provided below.

The primary revenue stream of an energy-capture speed bump is the electricity that it generates, measured in cents per kilowatt-hour (i.e., the local electricity rate). The system additionally adds value for customers by reducing reliance on fossil fuels for electricity, as well as improving safety in highly trafficked areas. Although the value of improved safety and environmental benefits are challenging to monetize, such benefits would be grounds for the electricity from this speed bump to be sold at a premium. In other words, a university's willingness to pay for electricity generated from this system would likely be higher than the local retail electricity rate, given the additional value offered by the system. For the sake of estimating the payback period for a scaled version of our prototype, we will base our per-kWh revenue on the NC retail electricity rate of 11.5 cents per kWh (*Find Energy*). Due to (1) the safety and environmental benefits of the speed bump, and (2) the fact that NC's electricity rate is low relative to the national average, we assume an effective revenue of 15 cents per kWh for our scaled system.

To calculate the product's payback period, the per-kWh revenue above is compared to the estimated cost of a full-scale system (i.e., using a 100 gallon tank pumped to 500 PSI). The cost to produce our current prototype amounted to $320.74, but this does not provide a good estimate of the total cost of a system at scale. Our prototype cost includes the pump and all components necessary to connect and direct air from the pump to the pressurized storage tank, but the cost of the tank itself is not included in this calculation due to the fact that we already had access to a tank. Had our team purchased a new tank, the total prototype cost may have doubled. Furthermore, labor, manufacturing, and capital costs are not included in the cost of the prototype system.

A summary of the estimated costs for a full-scale system are provided in the table below. For the component parts of the system, estimates are based on discounting the retail price of comparable parts to better match wholesale prices, as well as accounting for cost reductions associated with economies of scale. Capital, labor, and manufacturing costs are subject to greater error but are also estimated on a $/unit basis. For our full-scale system, we assume a 100 gallon air tank that reaches a maximum pressure of 500 PSI. We also assume a greater number of pumps, meaning that a larger volume of air is input into the tank with each compression of the speed bump. This is a major assumption given the issues that our team faced in terms of the pump we used in our prototype, but we assume that a full-scale system would have a pump that fits within the parameters of the speed bump and also has a much larger volume. It is reasonable to assume that the team could fit eight pumps into the system, each with twice the per-stroke volume of the pump that our prototype uses—i.e., each speed bump compression would add 16 times the volume of atmospheric air to the tank compared to one compression of our current prototype. The cost estimates are in the table below:



Full-Scale System - 100 gal tank @ 500 PSI Estimated Lifetime Cost ($/unit)		
Pumps	$	800
Tubing	$	100
Tank	$	800
Turbine/Generator	$	1,000
Other Materials	$	150
Manufacturing Costs	$	300
CapEx (per unit)	$	250
Planning & Installation	$	500
Maintenance	$	300
TOTAL COST:	$	4,200

Table 3: estimated lifetime cost ($/unit) of a full-scale system

A 100 gallon tank at 500 PSI would contain approximately 1.34 kWh of input work, which corresponds to roughly .67kWh of electricity, assuming a 50% power-to-power efficiency. For the sake of estimating electricity output, the payback period calculations assume that the system is able to achieve an average of one full tank (500 PSI) per day. Using the aforementioned willingness to pay of $.15/kWh, we can calculate a rough payback period for the full-scale system using the estimated *lifetime* costs above. Based on the line of best fit from the plot of tank pressure vs. compressions, it would take approximately 4,700 compressions to fill the 7 gallon tank to 500 PSI using our current pump. If we are able to increase our per-compression input volume significantly for the full-scale system (by using more pumps, each with a larger stroke volume), then it would be feasible to size the system such that the tank is filled an average of once per day. Assuming the system is sized to fill the tank an average of one time per day, the yearly revenue would be equal to:

$$.67kWh/tank * 1tank/day * 365\ days\ /\ year * \$.15/kWh = \$37/year$$

Earning revenue of $37 per year, it would take more than 110 years to pay back the cost of the system. Given that the operational lifespan of the system would certainly be less than that payback period, this system would not be economically viable.

To make this system economically viable, it will be necessary to drastically reduce costs or significantly increase system output. A payback period of 10 years would require $420 in annual revenue, which would correspond to a daily electricity output of roughly 7.7 kWh/day. If we instead assume that the system is sized to fill a 500 gallon tank to 500 PSI once per day, then the new annual revenue would be approximately:

$$3.35\ kWh/tank * 1tank/day * 365\ days\ /\ year * \$.15/kWh = \$183/year$$

At this rate, the speed bump would have a payback period of roughly 23 years. Although the economics are still challenging for this larger system, this payback period is within the realm of reason (albeit considerably longer than other clean energy technologies). By driving down system costs and taking advantage of policy incentives, it seems reasonable that a payback period of 10-15 years would be achievable for this technology.

The figure below plots work (kWh) as a function of pressure (PSI) for a 100 gallon, 250 gallon, and 500 gallon tank.

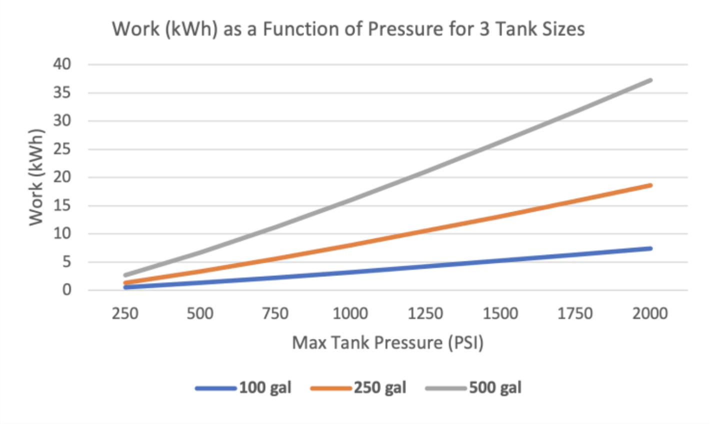


Figure 6 maps work (kWh) as a function of pressure for three tank sizes

Considering the results of this figure, a key area of focus should be maximizing the volume of air input to the tank per pump-compression. If the amount of air entering the tank during each speed bump compression can be significantly increased without proportional increases to the cost of the system, then the economics of this system could improve drastically. The cost and technical parameters of the specific pumps used in the system would be a major driver of the feasibility of this approach, and this should be a primary area of focus in commercializing this system. Leveraging economies of scale and government incentives may further drive down the system's costs, and the challenging economics of this product may be alleviated by the focus on university customers as the early target market; universities may have a higher willingness to pay for the product than assumed in the analysis above, given that the system generates carbon-free electricity, improves safety on campus, and creates educational opportunities.

An additional policy consideration that relates to the system's operating costs is the North Carolina Department of Labor's mandate that compressed air tanks need to be drained weekly "to purge water buildup" (NCDOT, 3). This creates an additional operating cost (OPEX) in the form of a salaried technician. This is a scalable cost since the more units there are in an area the lower the cost will be in terms of $salary/unit— since technicians will need to travel less far between units, and will be able to cover a large number of units each week. This is also an opportunity for monetization, since offtakers will need to pay a subscription cost for the ongoing service and maintenance— a large source of revenue for companies in similar hardware-related industries like elevators and commercial cooling. It will also be a source of skilled job creation, since "only those employees who have been trained to work with air compressor storage tanks will be allowed to operate such equipment" (NCDOT, 4). Additionally, there are favorable federal and local policy landscapes that could help us to both finance and commercialize our speed bump, including tax incentives, grants, and building codes.

Government Incentives

Since the speed bump system is chiefly pertinent to university systems, tax credits may not seem extremely enticing— since tax-free organizations do not pay taxes. However, this isn't necessarily the case.

Most solar PPAs are structured with two chief financiers— a Chief Sponsor and a 'Tax Equity Partner.' There are three different (extremely complex) financing mechanisms for this relationship: Partnership Flips, Inverted Leases, and Sale-leasebacks. The mechanisms involve different share classes, and the last two integrate put and call options. A mutual feature, however, is that the Tax Equity Partner puts forward about 35% of the capital and receives the tax deductions from the investment which they can use to offset tax bills from their other operations (*NortonRoseFulbright.com*). Meanwhile, Chief Sponsors invest more, and own a much greater share of the investment gains. Universities could co-opt this model by acting as the Chief Sponsor and bringing in a second party to help finance the speed bump, and in turn provide them with the tax deductions garnered. Alternatively, the university could serve the role of an offtaker in a PPA structure; here they could agree to buy electricity at a set rate in $/kWh for the lifetime of the speed bump while bringing a financier on board to pay for the infrastructure.

There are two kinds of tax credit programs that the speed bump could utilize; the Purchasing Tax Credit (PTC) program or the Investment Tax Credit (ITC) program. The PTC would provide a tax credit of 1¢–2¢ per kilowatt-hour for the first 10 years of electricity generation, while the ITC would provide a likely 20-30% tax credit (no less than 10%) for the investment cost of installing the speed bump (*Windexchange.com*). Due to the high CAPEX:kWh/yr ratio of the speed bump-system, the ITC program would be preferable. Financing mechanisms for a PPA would also need to use the ITC program, since the

Tax Equity Partners prefer an upfront reward for their investment. The exact rate is system-specific however, so the US government would need to recognize the speed-bump system and apply an ITC rate before it would materialize as a credit option.

North Carolina as a state has a very favorable policy landscape concerning solar energy, one of the reasons why it has the second largest installed capacity per-capita in the US. Unfortunately, the legislation for tax deductions is limited to solar and not all sources of renewable energy. However, this could be changed with lobbying in the future, as it is likely to be attributable to the natural resources of the state rather than legislative preference for solar.

While the state legislation is currently unhelpful, local governments in the area have implemented policies which could advance the speed bump's commercialization. The Town of Chapel Hill, for example, enacted an ordinance in 2004 (Sec. 5-121.) where all new buildings need to be LEED certified (*TownofChapelHill.org*). Integrating speed bumps in their construction everts would help developers and contractors to reach this level, since they'd be drawing less energy from the grid. Typically, PV is used to satisfy this ordinance, but our speed bump would also be a viable means to do so.

Additionally, The Federal Research and Development (R&D) Tax Credit provides a credit of 13% for "new and improved products and processes" (*RDTaxSavers.com*). Should we or someone else incorporate a company to improve and develop the speed bump technology we would be eligible to offset this amount against our costs. Furthermore, the US DOE is providing $127MM in funding for zero-carbon startups, provided through the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs (*Energy.gov*). The SBIR grant is the largest single provider for climate-tech entrepreneurs in the US, disbursing $2.5Bn each year. If the speed bump is seen as economically viable venture capital and angel investor funding could be other avenues to scaling up production; later, business loans would materialize as an option as well.

Conclusion

Implementing and scaling the speed bump system would bring a myriad of environmental and social benefits; even if its commercial application is constrained by limited power generation. Comparing the modeled promise of its Levelized Cost of Electricity (LCOE) against commercial renewables (PV, CSP, Wind etc.) is simultaneously necessary yet somewhat myopic. Here, it is —and will likely always be— a clear loser. While we developed an equation for assessing the key social benefits (avoided carbon and grid electricity prices) it doesn't consider the avoided cost of building transmission systems and grid connection (which is idiosyncratic to each system), as well as some key benefits. These key benefits include the ability to scale without the wild commodity price swings of key green minerals, and avoiding the ethical dilemmas of opaque supply chains. This would serve to entice administrators who are concerned about the child-labor implications of lithium-ion-systems, and investors who are concerned over price squeezes for cobalt, nickel, and lithium. Perhaps the strongest application of the speed bump-system is for potential loads that are adjacent to speed bumps but aren't yet wired into the grid (providing a strong opportunity for CAPEX avoidance). In this scenario, the speed bump-system LCOE would need to be compared against tiny solar LCOE— as they would both be operating in an island-grid system.

As mentioned earlier, the speed bump system is highly scalable, while occupying a niche and uncontested market. Marking up the cost of production while implementing subscription fees for maintenance offers a 'tried and true' path to monetization and future profits; with the entailing benefits of a warm policy landscape that provides a strong credit infrastructure for both product development and eventual ownership. An additional benefit of the proven scalability is the customizability of the system.

Manufacturing costs are strongly associated with air-tank size and the number of pumps. This allows us to meet the needs of various customers wishing to power variously sized loads with variable pricing. Overall, producing this speed bump on a mass scale is feasible, but will need much more future research.

References

NCDOT Staff.*“Safety Policy & Procedure, Air Storage Systems* - *CONNECT NCDOT.”* NC Department of Transport, https://connect.ncdot.gov/business/safety/SPP/SPP%201910.169%20Air%20Compressor%20Storage%20Tanks.pdf.

Leighton, Morgan. *“The Ultimate Guide to the Cobalt Market: 2021 - 2030.”* Crux Investor, 7 January 2021, https://www.cruxinvestor.com/articles/the-ultimate-guide-to-the-cobalt-market-2021-2030f.

Lawson, Michele. *“The DRC Mining Industry: Child Labor and Formalization of Small-Scale Mining.”* Wilson Center, 1 September 2021, https://www.wilsoncenter.org/blog-post/drc-mining-industry-child-labor-and-formalization-small-scale-mining

Energy.gov Staff. *“Production Tax Credit and Investment Tax Credit for Wind.”* Windexchange Energy.Gov, https://windexchange.energy.gov/projects/tax-credits

FindEnergy.com Staff. *“Electricity Coverage and Statistics in North Carolina.”* FindEnergy.com, 16 March 2021. https://findenergy.com/nc/

Chin, Lauren & Goulding, Charles. *“The R&D Tax Credit Aspects of Energy Related Startups.”* RD Tax Savers, https://www.rdtaxsavers.com/articles/Energy-Related-Startups

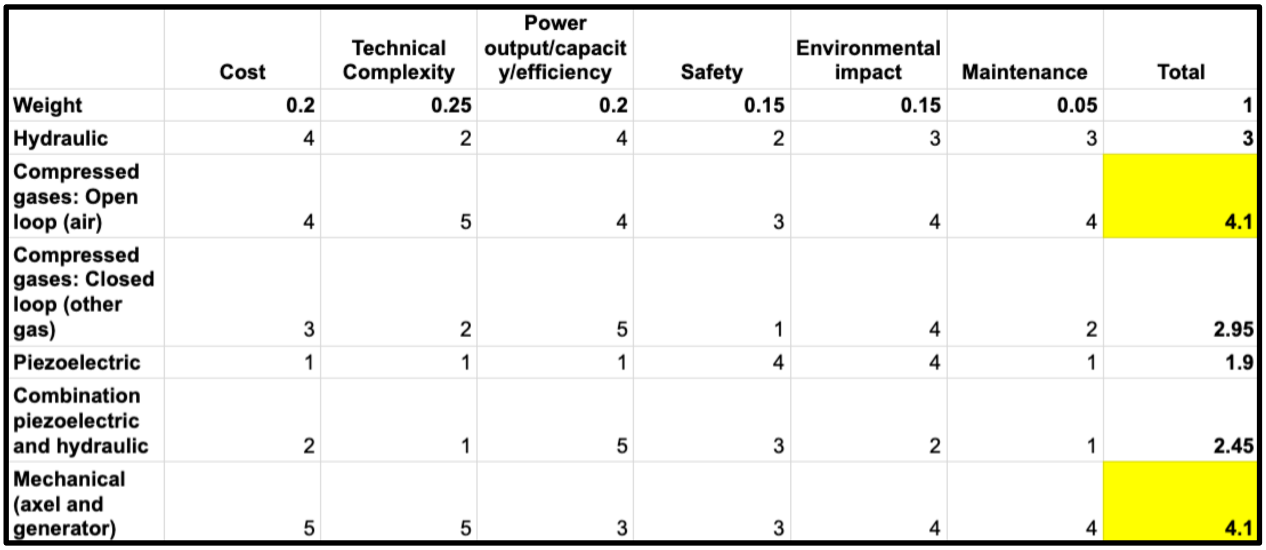
Office of Energy Efficiency & Renewable Energy. *“Small Businesses Awarded $8.9 Million in Building Technology R&D Funding.”* Energy.Gov, 3 August 2021, https://www.energy.gov/eere/buildings/articles/small-businesses-awarded-89-million-building-technology-rd-funding

U.S. Energy Information Administration Staff. “*State Electricity Profiles* - *Energy Information Administration.”* U.S. Energy Information Administration. https://www.eia.gov/electricity/state/.

Norton Rose Fulbright Law Staff.*“Solar tax equity structures.”* Project Finance NewsWire, Norton Rose Fulbright. 14 December 2021, https://www.projectfinance.law/publications/2021/december/solar-tax-equity-structures/

Chapel Hill Municipal Government.*“Town of Chapel Hill Code of Ordinances Chapter V. Article VII.”* 2004, https://www.townofchapelhill.org/home/showdocument?id=4954

Appendix A:



	Cost	Technical Complexity	Power output/capacity/efficiency	Safety	Environmental impact	Maintenance	Total
Weight	**0.2**	**0.25**	**0.2**	**0.15**	**0.15**	**0.05**	**1**
Hydraulic	4	2	4	2	3	3	**3**
Compressed gases: Open loop (air)	4	5	4	3	4	4	**4.1**
Compressed gases: Closed loop (other gas)	3	2	5	1	4	2	**2.95**
Piezoelectric	1	1	1	4	4	1	**1.9**
Combination piezoelectric and hydraulic	2	1	5	3	2	1	**2.45**
Mechanical (axel and generator)	5	5	3	3	4	4	**4.1**

Figure 1: Decision Matrix comparing technologies for prototype

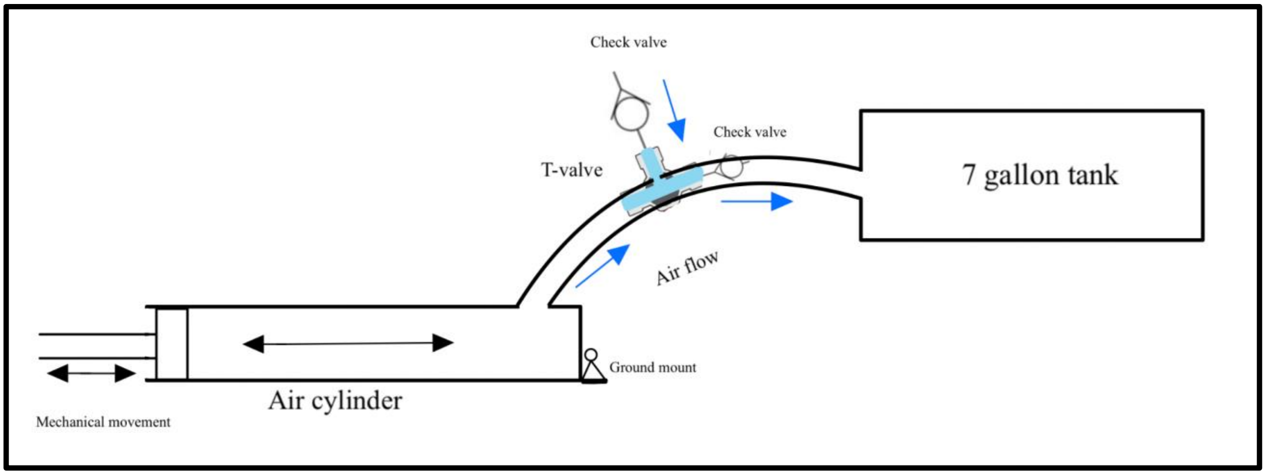


Figure 2: Schematic of inner speed bump design

Table 1: Specifications of components

Component	**Specification**	**Link**
High-Pressure Stainless Steel Tee Connector	1/4 pipe size 304 stainless steel	https://www.mcmaster.com/t-connectors/high-pressure-stainless-steel-threaded-pipe-fittings/

Compact threaded check valve	Male inlet/male outlet 1/4 pipe size 304 stainless steel seal 303 stainless steel body	https://www.mcmaster.com/check-valves/compact-threaded-check-valves/
Straight Adapter (1)	Hose × NPT/NPTF Male Threaded Pipe: ¼ pipe size ⅜” hose internal diameter 303/304 stainless steel	https://www.mcmaster.com/barbed-tube-fittings/hose-fittings-for-air-and-water/metal-barbed-hose-fittings-for-air-and-water/
Straight Adapter (2)	Hose × NPT/NPTF Male Threaded Pipe: 1/8 pipe size ⅜” hose internal diameter 303/304 stainless steel	https://www.mcmaster.com/barbed-tube-fittings/hose-fittings-for-air-and-water/metal-barbed-hose-fittings-for-air-and-water/
Straight Adapter (3)	Hose × NPT/NPTF Female Threaded Pipe: 1/4 pipe size 9mm internal hose diameter 303 stainless steel	https://www.mcmaster.com/barbed-tube-fittings/hose-fittings-for-air-and-water/metal-barbed-hose-fittings-for-air-and-water/
High-Pressure Soft Plastic Tubing	⅜” internal diameter Opaque gray 19/32” OD 10ft roll	https://www.mcmaster.com/reinforced-tubing/high-pressure-soft-plastic-tubing-for-air-and-water/
General Purpose Worm-Drive Clamp	5/16" Band Wd. × 0.023" Band Thick 7/16" to 25/32" clamp ID range	https://www.mcmaster.com/hose-clamps/general-purpose-worm-drive-clamps-for-firm-hose-and-tube-9/
Single-Acting Round Body Air Cylinder	Female 12” Stroke length 1.56” OD Universal mount ⅛” pipe size	https://www.mcmaster.com/air-pistons/single-acting-round-body-air-cylinders/stroke-length~12/mounting-style~universal/od~1-56/
Teflon tank	N/A	N/A
7 gallon tank	⅛ NPT threads	N/A

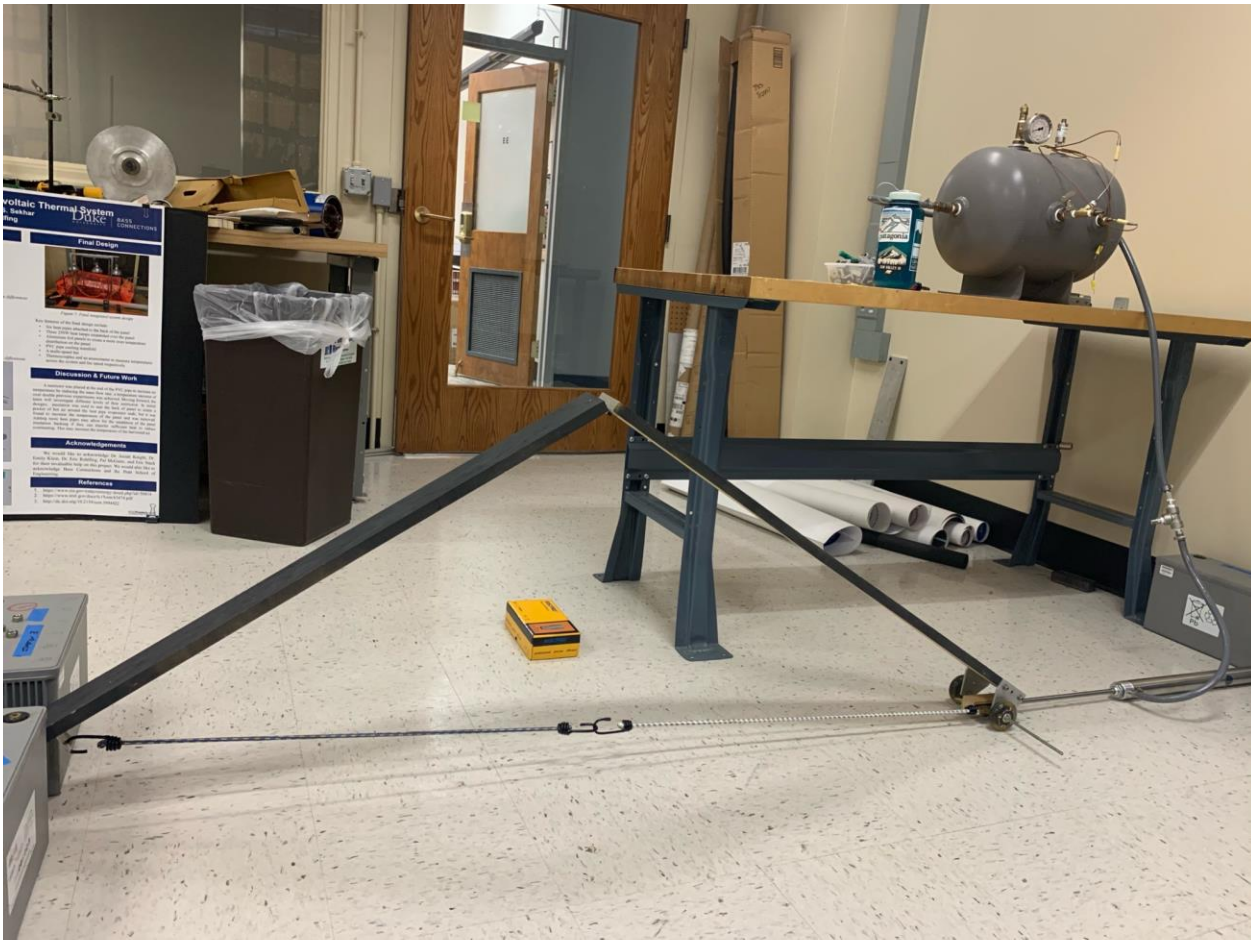


Figure 3: Rudimentary pumping mechanism

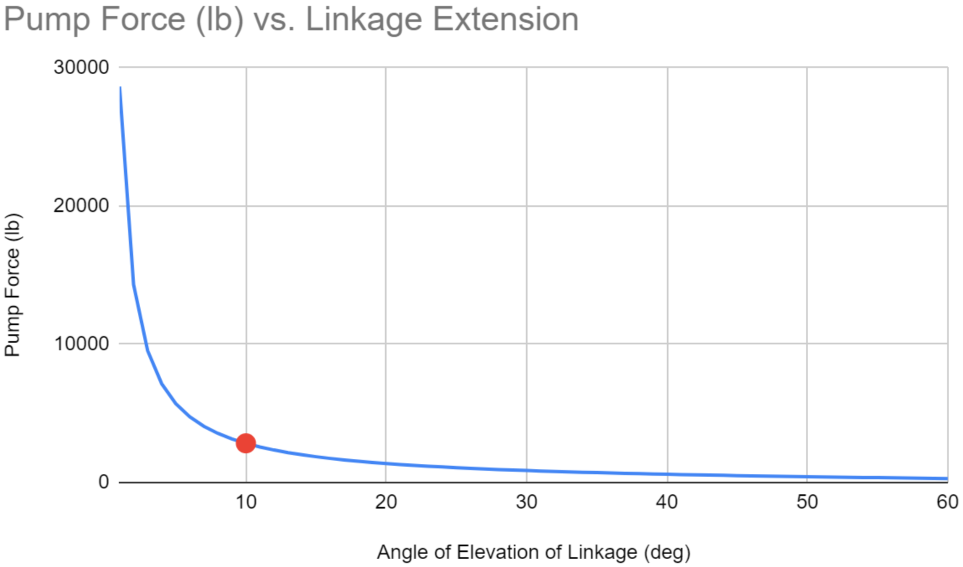


Figure 5: Force generated by pump piston at various degrees of compression of speed bump linkage

Appendix B:

Calculation of piston radius for optimal tank pressure generation:

At $\alpha=10°$, Pump Force = 2835.64 lbs

Assuming a desired pressure of 200 psi at the piston:

$$\frac{2835.64\ lbs}{\pi r^2} = 200\ psi$$

r = 2.12 in.

Piston radius should be 2.12 inches.

For a 12 in. pump stroke:

$V_{pump}=\pi(2.12\text{ in})^2(12\text{ in.})$

$V_{pump}=2.78$ L

Calculations done with aid from Dr. Knight and Dr. Rohlfing:

Amount of gas in tank with volume, VT, at final pressure, PT is:

nT = PT*VT/R*T. (don't worry about the units of n, because they won't matter)

This must equal the amount of gas transferred from the piston, which is:

NS*nP (where NS is the number of piston strokes) and nP is the amount of gas in the piston for each stroke, which is:

nP = PP*VP/R*T

where PP is the pressure in the piston (always atmospheric pressure) and VP is the volume of the piston.

Equating the two gives:

NS * (PP*VP/R*T) = PT*VT/R*T

Canceling R*T on both sides and rearranging gives:

NS * VP = (PT/PP)*VT

THUS, for a 50 gallon tank (189.271 L) rated for 200 psi:

NS = $\frac{200\ psi * 189.271\ L}{14.6959\ psi * 2.78\ L} = 920$ strokes required for full pressurization using 1 piston.