A Thesis Presented to

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Optimal Configuration for Multiple M.A.C.E. Turbines in Train Tunnel

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Abstract

Subways generate large pressure forces in subway tunnels while traveling. This wind energy can be harvested for power. The MACE (Mass Airflow Collection Equipment) turbine is an existing system that can be utilized to collect this wind energy. In initial testing done by WWT Tunnel, LLC, a ten foot turbine unit generated around 77.7 kWh, when the air reached a peak speed of 56.7 mph (25.35 m/s), in a total time of two and a half minutes. This turbine will likely be produced by several companies with their own variations, so the design for this turbine is not identical, however it is similar. That turbine is optimized here for maximum power output by analyzing the wake effect between turbines and the optimal placement and spacing along the length of a subway tunnel. One model is examined and then tested different placement configurations along the tunnel to minimize wake effect and optimize power output. This is done by modeling a turbine in SolidWorks and then using computational fluid dynamics modeling in ANSYS Fluent to simulate the airflow of the train passing. Washington Metro is an average subway station and this was used for the wind speed data so the configuration would be comparable for all subway stations. This research analyzes how turbines could be placed in a tunnel and in what configuration for maximum power output, by minimizing the wake effect. Simulation results indicate that a circular pattern works well for the turbines where the end of one is in line with the head of another, but placed 120 degrees clockwise along the wall. This produced only a slight reduction in wind speed between the turbines, on average 1-3 m/s (2-6 mph) difference. Further research should be conducted on more patterns of turbine placement and how the positioning would need to vary with increased wind speeds.

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Honors Introduction

Energy is all around us, and in everything we do. It is needed for electricity and manufacturing, to power our lights, and to run cars. Without energy our society could not function as it does today, and the world population could not be sustained. Worldwide, most of the energy consumed comes from oil and coal. These are effective, but are limited in supply and are non-renewable resources. These account for roughly sixty percent of the world energy supply. Natural gas accounts for twenty-five percent of the energy supply. The remaining fifteen percent is hydro, nuclear, wind, solar, and other renewable resources. The problem with this is that because oil and coal are non-renewable resources the world will run out of them in the foreseeable future.

World energy consumption is estimated at 18 terawatts (TW) annually. One TW is a trillion (10^{12}) watts. The estimated supply of extractable crude oil on the planet is approximately 2 trillion barrels. At current levels of use the world will use up the supply in under seventy years. This is not accounting for increased usage as the population increases, as the usage rate is closely tied with the population. What this means is that the supply of our main forms of energy will run out in the near future. Since more than half of the energy supply comes from coal and oi, other means of energy will need to be used if the world is to use energy in the same way and maintain current lifestyles. Increased reliance on renewable energy now would be an easy way to transition to a more reliable form of energy and prepare for the future.

Renewable energy gets the name renewable because the source of the energy is endless or easily replenished. Hydro, solar, and wind energy are the big forms of renewable energy with little environmental impact. While nuclear is considered renewable by some, it can be unstable, and once in place the facilities have to be maintained indefinitely as the nuclear material will be radioactive for thousands of years. Future energy supplies may be better off without nuclear reactors. Hydro, solar, and wind have little environmental impact, and can easily be removed or installed.

Hydroelectricity is electricity produced from hydropower. Hydropower is harvested from the movement of waves, waterfalls, rivers, dams, and any other form of water moving. The mechanical energy is converted to electricity. Solar collects the energy of the sun and converts the photon energy into useable power. Likewise wind energy is mechanical energy from the wind spinning the turbine/generator and being converted to electricity.

The environmental impact of a resource accounts for any pollution or byproducts, what materials are used to generate the electricity, disturbance to nature, and the ease of decommission. Solar and wind both have very little environmental impact. There is practically no CO_2 produced as a byproduct and the systems can easily be removed and leave little evidence that they were there. There are some critics who argue that these can be eyesores to the public, and that wind turbines are noisy. Also wind turbines are known to chop birds that fly through their path. These are all true, but are minor when compared to nuclear plants. Nuclear power production produces a radioactive byproduct and can be very hazardous. The site and the radioactive waste remain indefinitely as radioactive material takes thousands of years to become stable. So once in place the nuclear plant will be permanent. So by comparison this makes wind and solar much better alternatives. Hydro is very similar to solar and wind; the main difference is that hydro is harder to decommission, and has negative effects on water flow sometimes. Barrages kill fish and other aquatic life often as the water flows through the blades the fish do too. There are some measures to reroute aquatic life, but they are not always effective. By examining these criteria, it is evident that solar and wind are very green sources of energy collection with very small environmental impacts.

The main issue with renewable energy supplies is that the energy cannot be easily stored, so it has to be used as it is produced. There are flywheels and dams but they are not viable solutions. Energy storage is another problem that will need to be solved as the use of renewables increases. There are few methods of storing energy and none are very efficient. More methods of collecting renewables need to be found so that as renewables transition to the main energy supply, the energy can be stored for use during peak energy usage times instead of being produced and used immediately. Otherwise this would lead to energy shortages and power outages during peak energy usage periods throughout the day. The potential for renewables as a viable source is there, but all the components for consistent energy production need to be implemented. Renewable energy is virtually limitless, but most of it goes untouched.

The potential of these renewable resources remains untapped, but the possibilities for future energy supplies remains unlimited. Harvesting wind energy in different forms besides turbines in the sky would be one possible way to do this. Wind power is also generated from the movement of cars, trains, and other vehicles as they push through the air. In subway tunnels there is an increase in pressure as the subway enters the tunnel and forces the air around it, and up the tunnel. Harvesting this wind energy generated by the subway passing through the tunnel is a possible source of energy supply for the future. It could also be applied to trains passing through tunnels inside of mountains as well.

Research has been done on the potential of the wind energy that is generated by subways moving through tunnels. WWT Tunnel LLC is a company that developed a prototype of a MACE (Mass Airflow Collection Equipment) turbine that can be installed on the walls of a subway tunnel, and the spinning from the airflow as the train approaches and passes the turbine would generate electricity. This electricity can be used to power facilities in the subways or nearby homes. The potential is there for a lot of energy to be collected daily. Subways are heavily relied on in many metropolitan areas and would be an easy way to benefit off a frequently generated wind energy.

The initial trial run for the MACE turbine was in Los Angeles Metro in California. The subways here reach up to seventy miles per hour, and that was sufficient to produce energy. The ten foot turbine was in place for ten days and in that that time it averaged a production of 77.7 kilowatt hours (kWh) per day. As is, that one turbine would generate enough energy yearly, approximately 28,000 kWh, that it could power twelve homes in California for one year.

This is only a ten foot section of MACE turbine. More energy could be collected if these were installed in subways and train tunnels worldwide, and if multiple could be installed in one tunnel to maximize the energy production. The focus of this study is maximizing the energy output by finding the ideal configuration and spacing for these turbines in a subway, so that the maximum wind speed can be collected each time, with little influence from wake effect.

When wind passes through a turbine the energy goes into spinning the turbine and the wind force going out the other side of the turbine expands outward (increasing area), and is less powerful as a result. If turbines were placed too closely together the turbines would have less and less force going through the next one, until some of them would not be spinning or collecting any energy from the wind movement. This can be prevented by leaving enough space between turbines so that the wind speed builds back up and the force going into the next turbine is strong enough to generate power from.

This is a concept currently being tested by this company. Since initial results are very promising it is expected that other people and companies will want to expand on this idea of power generated from trains. So the design used for the simulations here is not identical to the MACE turbine, but based off of this design.

The design of the turbine is very aerodynamic. The edges of the turbine frame are rounded. The center beam supports the blades, which are actually fourteen mini turbines spaced in a row such that the air flow causes them all to spin at the same time. The open frame of the turbine allows air to pass through so that the maximum air flow is hitting the blades of the turbine and maximizing the power output.

This design will be used to find the ideal placement for multiple tunnels to minimize the wake effect between turbines. By finding the ideal configuration for these turbines in a subway tunnel the pattern can be implemented for future turbine installations and allow for maximum energy output.

Background

Subways are one of the most effective ways to transport people within metropolitan areas, however as the population grows, so does their usage, and their subsequent energy usage. As fossil fuel supplies are depleted it is important to increase the usage of renewable energy sources to maintain power supplies. Power can be generated from the wind force of the subway moving through the subway tunnel and if this energy is harvested it will help meet energy needs with a clean form of energy. The WWT TUNNEL LLC has started to address the possibility of harvesting the energy generated from subway tunnels with their MACE turbine, which is made of recycled materials and can be installed on any subway tunnel wall.[8] Their preliminary trials show power can be generated at much lower speeds than expected which means this turbine can work in any tunnel.[12] With further studies on this turbine and by figuring out the ideal placement for multiple turbines they can be placed in any subway tunnel in the world and provide energy to reduce local fossil fuel consumption.

Subways generate pressure in the subway tunnel while traveling. When a train enters a tunnel at high speed, the air inside the tunnel is compressed due to the piston effect, and the pressure suddenly increases because of the compressibility of the air, and mobility of the air is limited by the boundaries of the tunnel.[8] If the air velocity in the tunnel is constant then the pressure of air inside the tunnel is directly proportional to the distance from the tunnel's entrance upon the train entering the tunnel.[16] This compressed air inside the tunnel propagates through to the other end of the tunnel under the influence of unsteady viscous effects, which change as the train passes through as the pressure is higher in front of the train and lower behind the train.[1] This changing pressure force can be harvested for energy to power lights and systems of the station and nearby locations, and to offset spikes in usage from the subways passing through.

To maximize the power output of the wind turbines in these train tunnels, the wake effect will need to be analyzed since multiple turbines will be placed relatively close to each other. Wind turbines influence other turbines nearby aerodynamically. As energy is extracted from the wind the turbulence is enhanced and the wake flows into the next turbine altering the wind speed and lowering the amount of energy that could be potentially extracted.[5] By examining this the wake effect can be mitigated by placing the turbines far enough away from each other that the wind speed going into the turbine is fast enough to produce power. The distance may also be decreased by altering the placement of the wind turbines in the tunnel so that they are not linearly placed along the length of the tunnel and the air will flow more freely from one turbine to the next as the train moves.

WWT TUNNEL LLC has developed the MACE turbine to collect this energy generated by the subway's movement. They designed the turbine to be tested in LA Metro where the results were greater than expected. Image 1 shows the turbine being installed.

Image 1: MACE Turbine

The ten foot turbine was in place for ten days and in that that time it averaged a production of 77.7 kilowatt hours (kWh) per day. Figure 1 below shows the average power generation per TIE (train initiated event) in watts.

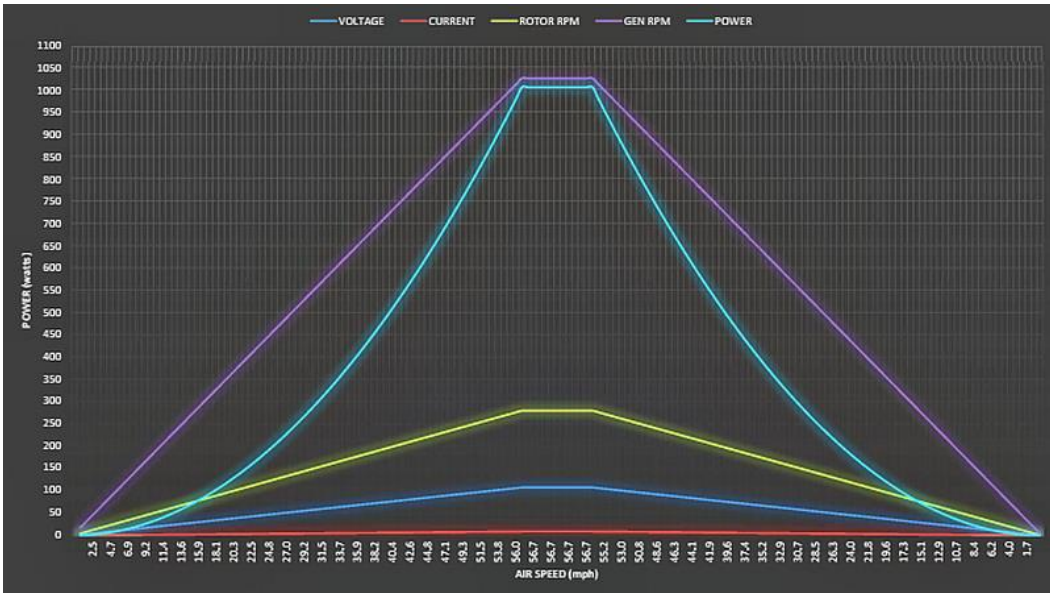


Figure 1: Average Power Generation per TIE (Watts)[8]

The potential for a lot of power is evident from this study, and by maximizing the number of turbines the power collected can be maximized too. The adaptability of this turbine to any subway tunnel will allow for wind energy to be collected in any subway worldwide, and by increasing the use of renewable energy will lessen the dependence on fossil fuels. Using SolidWorks, a model was designed of the wind turbine. To analyze the MACE turbine's performance computational fluid dynamics (CFD) simulations were used in ANSYS to measure the wake effect between turbines and the ideal placement of the turbines in the tunnel so the airflow through them can be maximized, and the spacing optimized for maximum power output. The ideal configuration can be applied to all future uses of the turbine and make installation patterns universal.

Methods

To conduct this study the wind turbine had to be recreated for simulations and analysis. The original engineering drawing for the turbine was unavailable for use, so the dimensions for the Solidworks turbine was obtained from Image 1 above. Knowing that the turbine was ten feet in length, from publications, the rest of the dimensions could be extrapolated proportionally. The turbine blades were very hard to produce and because of that a blade similar to what was needed was used from GrabCad. Using these extrapolated dimensions and the blade file an assembly was made for the turbine, shown in Images 2, 3, and 4 below.

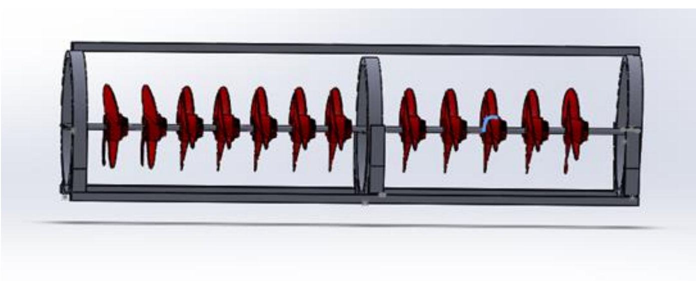


Image 2: Side Profile of Turbine

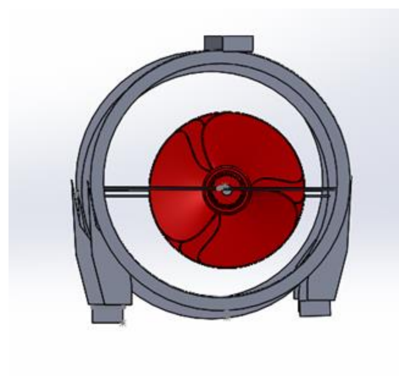


Image 3: Front View of Turbine

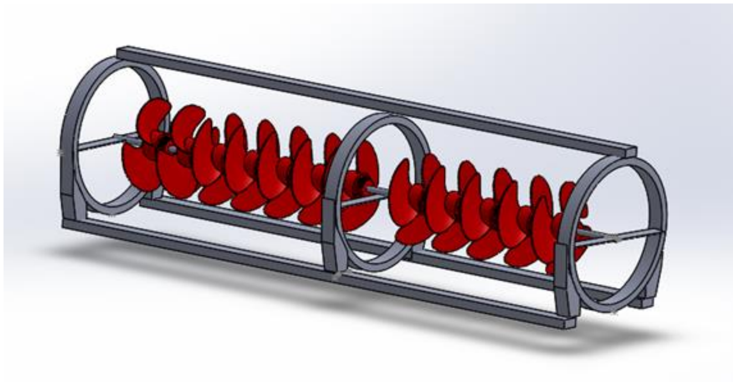


Image 4: Projected View

The mesh that was used had to be created large enough that ANSYS could perform the calculations because with large objects such as this turbine, the default on the number of nodes is quite high. A mesh was generated using a node size of 0.1 meters, this resulted in 27,000 nodes for the simplest simulation and 100,000 nodes for the most complex. The wind speed used for these simulations was 70 mph (31 m/s) which was an average subway speed shown in several of the papers. The conditions used to set the constraints for the analysis were that the inlet flow was velocity, and the outlet flow of the analysis boundary was pressure. The enclosure for the simulation served as the boundary of the train tunnel walls. 100 iterations was the input each time so that the software was approximating the results similarly each time. Then the velocity was calculated after the air flow through each of the turbines so that the impact of the wake effect could be compared as to how fast the air is going into the next turbine. Figure 2 below shows the impact of wake effect on turbines.

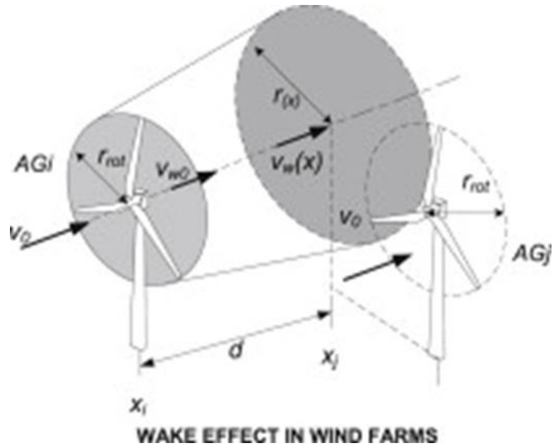


Figure 2: Wake Effect Between Turbines[7]

The velocity going in is spread over a larger area going through the turbine, as the blades push the air outwards. This means that the pressure force is lessened making the force going into the next turbine weaker, represented as an equation as P=F/A.[7] The main criteria for analyzing the wake effect here was the air velocity (pressure force) going into the next turbine. All other variables remain constant. The equation for calculating power from a wind turbine is

$P=0.5\rho\pi r^2 v^3 \mathcal{E}/1000$, where

P=power in kilowatts
ρ=air density in kg/m^3
r=radius of blade span in meters
v=air velocity in m/s
$\mathcal{E}$=efficiency

Since velocity is the only variable that changes, and all the other variables remain constant, the equation can be simplified to

$P=v^3\alpha$ where α is all the other variables combined as a constant.

Finding a configuration where the wind speed is constant between turbines will result in the maximum power output. Several of the tested configurations are included in the next section.

Results

The first iteration of the simulation is the MACE turbine by itself to demonstrate the air flow and speed reduction by the air passing through the turbine. This also serves as a comparison for the iterations with multiple turbines.

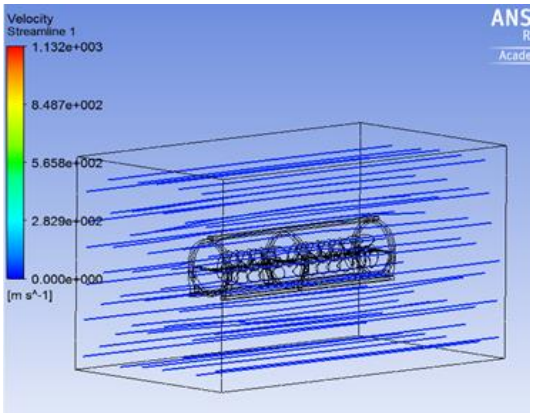
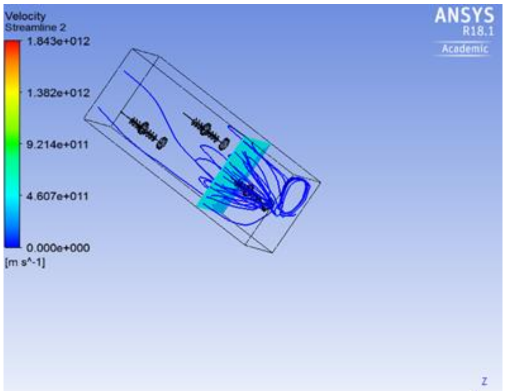


Image 5: Single Turbine Wind Speed

Image 5 shows the wind speed around one turbine is able to flow smoothly, and there is little disturbance. In the next iteration three turbines were configured in a circular way, and staggered like being placed down a train tunnel. The turbine had to be simplified at this point as the files were becoming too large to process, so the frame was simplified further. The turbines were staggered so that where one turbine ended the next one was placed at the end of that one, but clockwise around the tunnel 120 degrees apart.



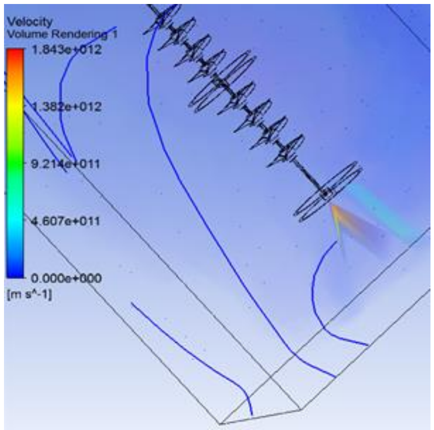


Image 6: Flow Around Turbines

Image 7: Flow off End of Turbine

The flow was decreased going through the turbines in this configuration, but the spacing seemed reasonable by only reducing the speed by 1-3 m/s (2-6 mph) on average. This configuration could prove useful. Future testing will be done where the spacing is slightly increased until results are idealized.

For the third iteration the turbines were placed so they were in pairs on alternating sides of the tunnel. The results for this one were not good as the wake from the turbines flowed together in any linear pairing as shown in Image 8.

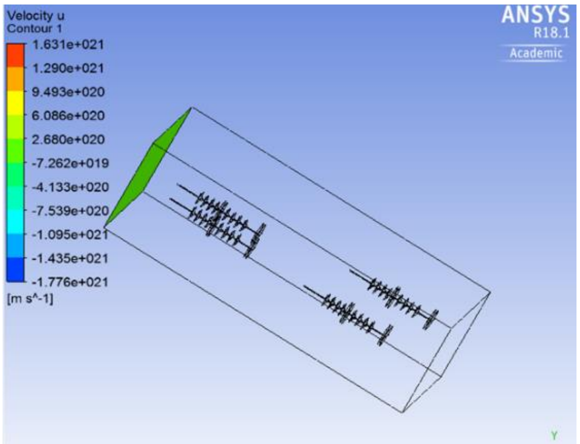


Image 8: Linear Pairings of Turbines

This was expected though, as the spacing and pairing puts the turbines too close for the wind to strengthen, and the paired turbines are sharing airflow at that proximity.

Discussion

The results of these simulations show that the ideal turbine placement to minimize wake effect is a circular pattern for the turbines, where the end of one is in line with the head of another, but placed 120 degrees clockwise along the wall. This staggering of the turbines produces only a slight reduction of wind speed through the turbine, and would allow for the maximum power output. The reduction observed was on average 1-3 m/s from 30 m/s as the input velocity. This was maintained from turbine to turbine and little wake effect was observed. The ideal production would maintain the 30 m/s input velocity and making the power output 27000α. At 25 m/s the power output is 15625α. It is important to note the change because the wind velocity is cubed in the calculation, even the smallest change greatly changes the power output. So that is why it is important to complete more analysis on the turbine configuration and air flow.

It is important to note that there are high speed trains and that future analysis could be conducted on trains going at much higher speeds, and through tunnels with more than one train track. There are many modifications that can be made and investigated at a future time, but this study focused on the basics to get an idea of the configuration that would provide maximum power.

Conclusion

The purpose of this study was to analyze the airflow around MACE turbines and find the configuration that would minimize wake effect so the power output would be maximized. The results show that staggering the turbines around the tunnel at 120 degrees clockwise from each other, head to tail, produced the least amount of wake effect. More modifications and analysis will be made at a future date, but this serves to advance knowledge of the MACE turbine and the aerodynamics surrounding it. By installing MACE turbines in train tunnels, energy can be collected frequently from train movement and reduce the impact of using trains. This will be a more sustainable practice, and one railway closer to creating a greener future.

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