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Feasibility Study of a 10 GW High Altitude Wind Energy Generation Station in New York State

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ABSTRACT

High altitude winds offer an enormous dense layer of energy over New York State, which can be considered as a cheap energy resource. This layer of energy not only can sufficiently supply this state, but also can supply all the U.S. energy needs. In this paper a High Altitude Wind Energy Generation Station (HAWEGS) with rated power of 10 GW over Catskill's mountains in the New York State is modeled and designed. The HAWEGS consists of an array of Airborne Wind Energy Generation Systems (AWEGSs). To achieve a smooth electrical energy generation during the year with a high capacity factor, the HAWEGS is configured as three interconnected sections spaced at the same longitude. The optimum performance heights of the AWEGSs in all the sections were found. Moreover, a detailed electrical system including power transmission and energy storage was designed. Three-month resolution and annual performances of the HAWEGS were presented. The project cost and electricity price were estimated. Also, risk management for addressing the highlighted problems was presented. It was shown that in spite of fossil fuel, extraction of high altitude winds using the HAWEGSs can decrease earth-surface temperature, addressing the global warming. Finally conclusion and perspective were presented.

KEYWORDS: AWEGS, HAWEGS, high altitude winds, Jet Stream, Climate model.

INTRODUCTION

The oil resources are expected to last only for the next 50 years, and the coal will last until the end of the century, according to the International Energy Agency's (IEA) findings published in June 2006 by the Global Wind Energy Council (GWEC) and Renewable Energy Systems Limited (RES). By 2030, when the oil and gas are supplying 60% of world's energy, production will lag demand by an estimated 18%, originated in the rapid rate of energy consumption. The earth atmospheric layers function like an energy converter, converting the solar energy and kinetic energy of the earth to the low and high altitude wind energies. The low altitude wind energy is estimated about 72TW, which is five times higher than global energy demand. The global energy demand is estimated about 13TW [1]. Thus, Wind energy as a renewable form of solar energy is the best choice to fill the future electricity generation future gap between production and consumption.

Although more attention recently has been paid to development of low altitude wind turbines for extraction of low altitude wind power, these wind energy systems can trap only about 30% of the low altitude wind energy. These systems have several drawbacks including aesthetic impacts, high land occupation, high installation cost, need to high amount of structural materials, and low capacity factor originated in inconsistence nature of the low altitude winds speed with variable direction.

In contrast, high altitude winds are faster and more persistent with more constant direction. High altitude winds contain about 1000 TW energy which is 100 times bigger than global energy demand [2]. High altitude winds include two main jet streams including the polar front jet altitudes in range of 7 to 12 km, and the sub-tropical jet at higher altitudes of 10 to 16 km located at 30 and 40 deg, North and South [2]. Although due to oil crisis in 1973, more attention was paid to high altitude wind energy generation; this technology is in its early stages yet, and has not been developed as much as ground-based wind turbines technology. There are only small

companies like KiteGen, Magenn Power Inc., Sky WindPower Corp., and Joby Energy, which are mainly supported by private investors, are working on high altitude wind energy generation. These companies have proposed innovations in high altitude wind energy generation systems. But, an organized plan and movement to achieve a deployable HAWEGS has not been appeared yet.

United States is one of the countries who are blessed enough to have strong high altitude winds. Some parts of the U.S. are under the main jet streams which cover some states such as New York, Boston, and California. These states are under a vast dense layer of energy which is just few kilometers away from the users in these states.

Thus, it is essential for the upper atmosphere energy resources to be studied more, for both the feasibility analysis of deploying the HAWEGSs, and development of the AWEGS technology.

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In this paper, feasibility study of a HAWEGS over one of the regions, Catskill, in New York State for extraction of high altitude wind power was carried out. Analyzing high attitude wind data provides preliminary information for deployment of a HAWEGS, as well as the required technology. The scientific contributions of this paper can be summarized as follows:

1. A multi-stage procedure for feasibility study of HAWEGSs was proposed.
2. Project costing and risk management for the HAWEGS were presented.

The reminder of this paper was organized as follows: In section II, site selection including selection of a safe area with minimum airline rout density, maximum wind power density, and minimum distance to the national power grid was presented. In section III, models and designs of the AWEGSs and HAWEGS was presented. Also, a configuration for the HAWEGS was proposed. In section IV, high altitude winds were analyzed, and the resulted vertical profiles were presented. In section V, optimum heights for operation of AWEGS were presented. In Section VI, the HAWEGS' performance including annual and three-month resolution productions was presented. In section VII, cost of the HAWEGS and electricity price of its output power were estimated. In section VIII, risk management to highlight the problems and suggested solutions were discussed. Finally, in section IX, the conclusion and an outlook over the future works were presented.

SITE SELECTION

Similar to ground-based wind farms, selection of a suite site for the HAWEGS depends on several factors should be considered.

A. *Airline Routes Cross Over*

The airline route are one of critical factors will mainly limit the selection of the site. Thus, the first step is selection of a region with minimum interface with the airline routes. The New York map and the corresponding air line routes over the New York State were shown in Fig. 1(a) and (b), respectively. The Catskill Mountains are the best place with minimum air route density.

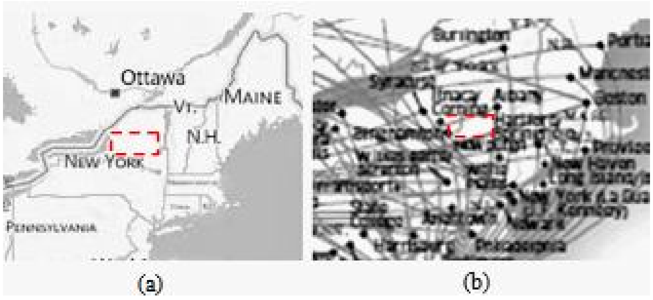


Figure 1. (a) New York State. (b) The correspoding air line routes.

B. *Site Geographical Description*

The Catskill Mountains is an area in New York State, where located at northwest of New York City and southwest of Albany. This area with a surface area of 15.259 km^2 occupies a geographical zone between 42 and 44°N latitude and between 74°W and 77°W longitude with maximum elevation of 1,274 meters. The upper atmosphere in Catskill Mountains is significantly under influence of the main jet streams.

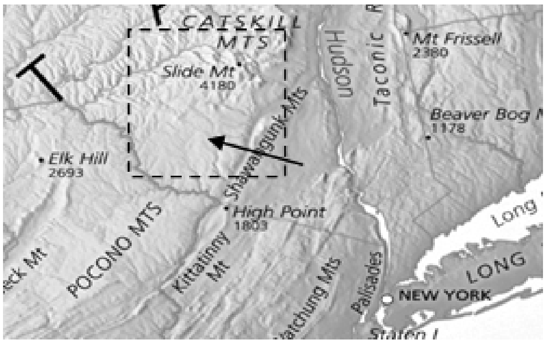


Figure 2. Catskill Mountains at the north of New York state

Catskill Mountains are near to a power grid. A substation allows injecting the harnessed power to the national electric grid. This substation is located near to Catskill Mountains. The injected power by this substation, can power all New York energy demand. The substation specifications were given in Table I.

TABLE I. SUBSTATION CHARACTRISTICS

Name	Ratio	Trans. No	KVA	Total KVA
CATSKILL	230:63	4	125	250

In national regulated electricity market, System Impact Study (SIS) is required to connect a new dispatchable generation unit to the grid [3].

HAWEGS TOPOLOGY

C. Wind Turbine Design and its Model

A HAWEGS consists of an array of AWEGSs operating at altitudes. Due to operation of the AWEGS at altitudes, the generated power should be transmitted electrically to the ground via a conductive tether. It can be molded as a generation unite anchored to ground via a transmission cable as conceptually was shown in Fig. 3.

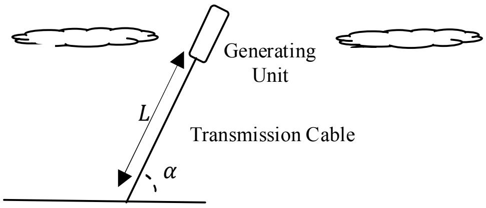


Figure 3. Concpetual repereseentation of a AWEGS.

Spite of ground-based wind turbines, the AWEGSs with ability of changing their pith angle can highly reduce effect of the gust load. The voltage of the AWEGS is mainly affected with its operation height. For higher heights, a longer power transmission cable, conductive tether, is required. Thus, higher voltage will be required to reduce electrical power loss. Since, according the next section, the AWEGSs plan to operate at height of 8km; voltage can be chosen in the range of 11Kv to 25Kv. Power curve data of a AWEGSs based on obtained experimental data on a small prototype which presented in [4] was charted in Fig. 4. The cut in and cut out speeds are the main parameters in the design of an AWEGS. To achieve an A HAWEGS with rated power of 10GW , 7700 numbers of the AWEGS was needed. The specifications of the AWEGS were given in Table II.

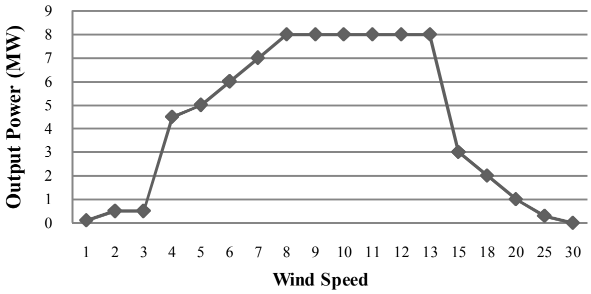


Figure 4. Power curve of AWEGS.

TABLE II. AWEGS SPECIFICATIONS

Quantity	Value
Rated Power	1.3 MW
Shipping Weight	130.000 lbs
Volume of Helium	20.000 m^3
Tether Height	8 Km
Start-up Wind Speed	2.5 m/sec
Cut-in Wind Speed	3.0 m/sec
Rated Wind Speed	20.0 m/sec
Cut-out Wind Speed	50.0 m/sec
Maximum Wind Speed	52.0 m/sec
Life Cycle	10 to 15 Years

D. Wind Turbines Configuration

Although based on the type of used AWEGS, arrangement of the AWEGSs, and the distance between adjacent AWEGSs, involves in a different optimization problems, at this preliminary stage, a simple arrangement of AWEGSs was considered as shown in Fig. 5(a) and (b).

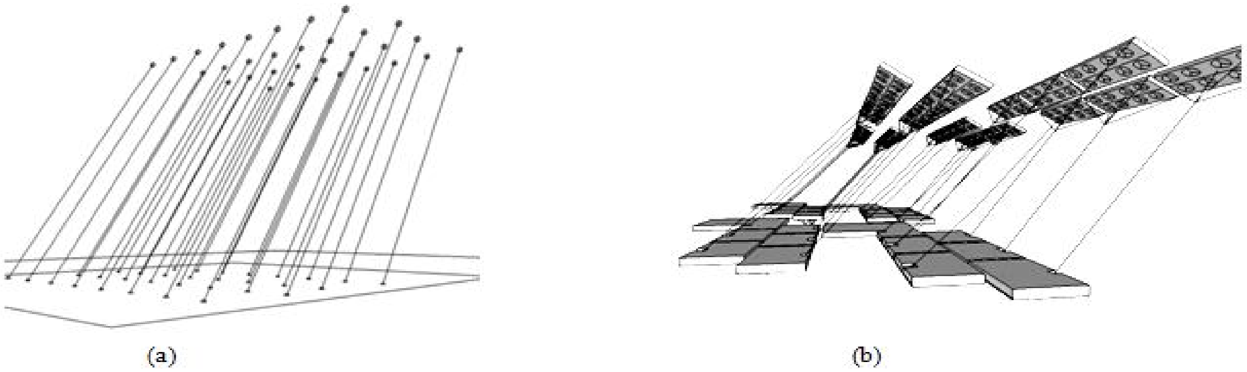


Figure 5. (a) Simple side view reperesentation of the HAWEGS. (b) HAWEGS consist of an array of the AWEGSs.

E. *Addressing the Intermittency*

Due to uncetain nature of wind power density, and its local and sesonal variablity, two methods including inconncting the distributed wind power system, using hydrogen production and storage, have been proposed. But, a hybrid of hyrogen storage, and interconnected sections provide a more smooth output power with lower cost.

1) *Sectionalizing*

Since jets streams tend to shift attitudinally periodically, to have a smooth generation during year, a geographically dispersed configuration of HAWEGS at same lontitude should be chosen. But, this configuration allocates a great area of land. Thus, the HAWEGS was sectionalized to three sections at same lontitude, and interconnected via ground-based transmission lines, as shown in Fig. 6. This configuration can highly alleviate the local variability in annual wind power generation .

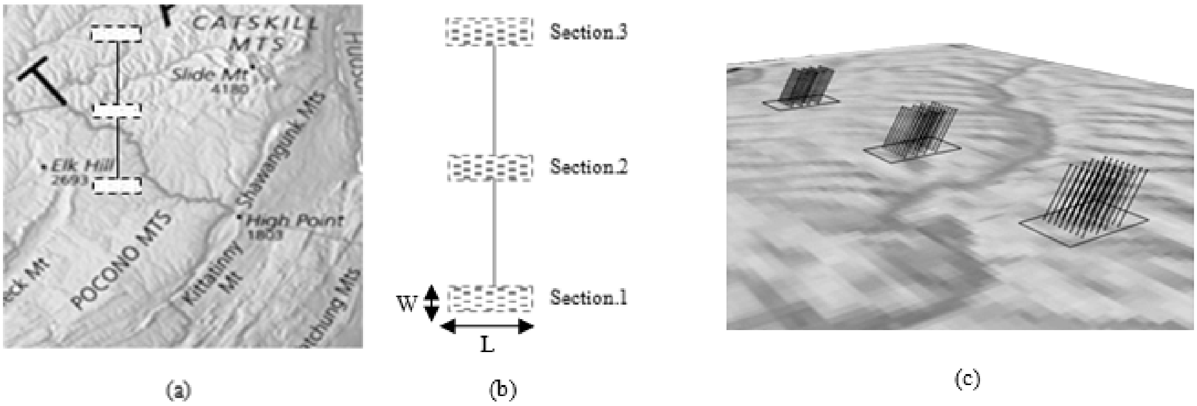


Figure 6. (a) The HAWEGS was sectionalized into three interconnected sections.
Figure 7. (b) represntation of the sectionlized HAWEGS.(c) Three sections of the HAWEGS

Each section include 7700 number of AWEGSs Length, L, and width, W, of each section are 10 and 15 kilometers, espectivelly, as shown in Fig. 6(c). Each section include 2566 number of the AWEGSs.

2) *Hydrogen Storage*

Hydrogen can be produced using water electrolysis process. Based on the profile of the United States power demand, especially New York State, in windy month of winter the production will exceed the demand. Thus, hydrogen can be produced and stored to be consumed in the summer. It was obviously that a higher average annual wind speeds could lead to a lower hydrogen prices. The generated power by the HAWEGS can be sent to a remote electrolyzer via a gird. After production and storing of hydrogen, it can be used for both generations of electricity and transportation fuel uses as shown in Fig. 7.

It is essential to construct equipments for hydrogen production underground. The designing hydrogen storage based on the rated power and capacity factor of the HAWEGS, which will be computed in section IV.

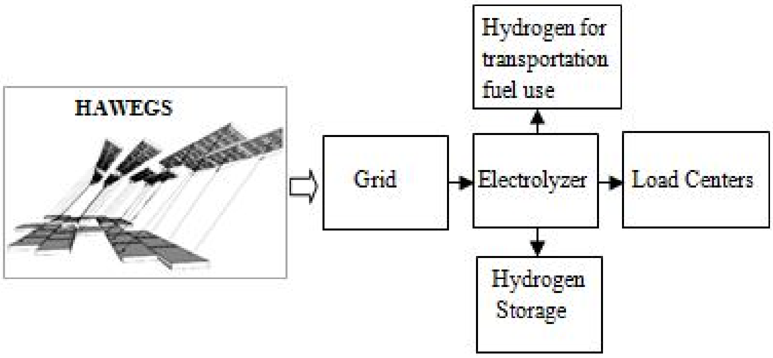


Figure 8. Block Diagram of prodcutin of hydrogen for both the electrical energy generation and transprotaion fuel uses

HIGH ALTITUDE WIND ANALYSIS

27 years of wind data from the NCEP/DOE global reanalyses [5] are used for assessment of high altitude wind resource in the Catskill Mountains. Since wind energy systems cannot trap energy in the highest and lowest wind speeds, in [5], it was not focused on mean values, but somewhat on a few percentiles including 50th, 68th, and 95th, which indicate the wind power density occurrence probabilities exceeded on 50%, 68%, and 95% during 1979 to 2006.

F. New York City Vertical Profile

The annual wind power density at altitudes in range of 0-12km for three occurrence probabilities exceed 50%, 68%, and 95% for the Catskill Mountains are shown in Fig. 8.

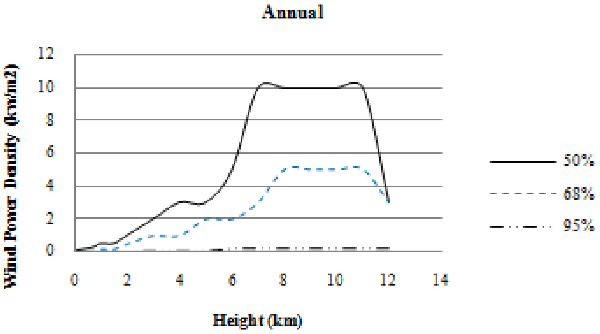
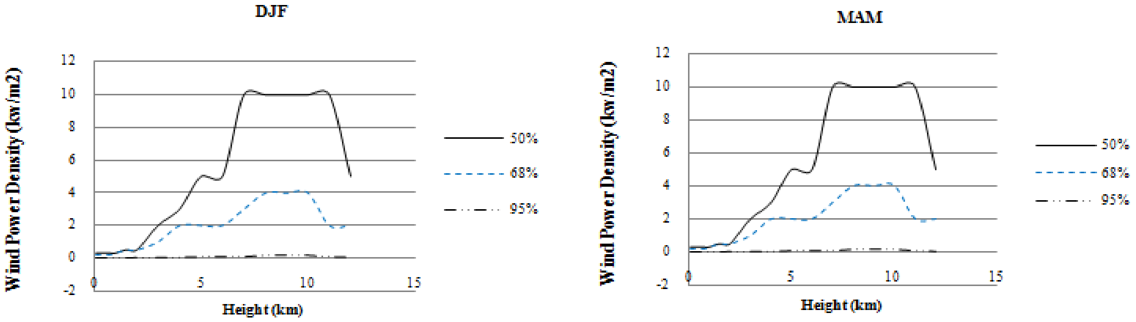


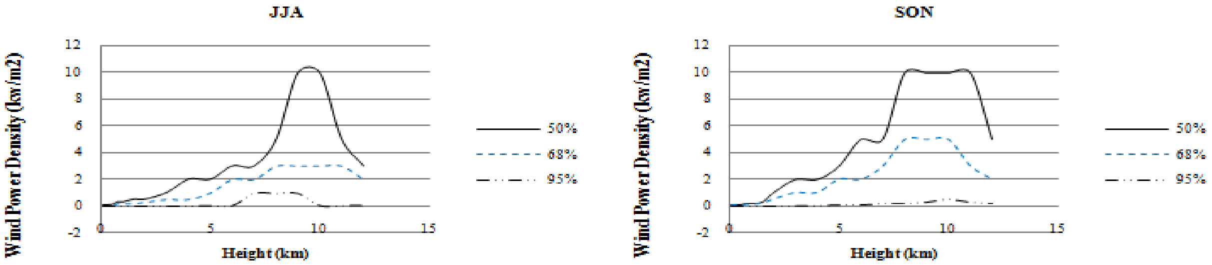
Figure 9. Annual wind power density, for occurance probabilities exceed 50%, 68%, and 95% during 1979 to 2006 as versus altitude from the NCEP/DOE reanalyses [5].

Also, the wind power density at altitudes in range of 0 to 12km for three occurrence probabilities exceed 50%, 68%, and 95% were reported, and are charted with 3-month resolution as shown in Fig. 9 and 10. The statistic resolution is chosen three-month since the resolution of available data in the [5] was 3-month.



(a) (b)

Figure 10. Wind power density versus height at monthes of Decemeber, January, and February, for occurance probabilities of 50%, 68%, and 95%. during 1979 to 2006 versus altitude from the NCEP/DOE reanalyses. Wind power density, at monthes of March, April, and May for occurance probabilities exceed 50%, 68%, and 95% during 1979 to 2006 versus altitude from the NCEP/DOE reanalyses.



(a) (b)

Figure 11. (a) Wind power density, at monthes of June, July, and August, for occurance probabilities exceed 50%, 68%, and 95% during 1979 to 2006 versus altitude from the NCEP/DOE reanalyses.(b) Wind power density, at monthes of September, October, and November, for occurance probabilities exceed 50%, 68%, and 95% during 1979 to 2006 versus altitude from the NCEP/DOE reanalyses.

Excluding the monthes September, October, and November, the highest wind power densities are found at altitudes between 8km to 10k m while at monthes October, and November the highest wind power densities are found at altitudes between 9 to 10k m. Moreover, it can be seen the winter, wind power density patterns is similar to the annual patterns.

It can be observed that the high altitude wind power density over the Kastkill Mounatins, is higher than 10 kW/m^2 for more than 50% of the time. It should be noted that, the since the three sections were considered to be located at three diference locations, the extracted wind data from [5] is more reliable.

OPTIMUM OPERATION HEIGHT

As the height increases, the wind speed increases. But, after a specific altitude, due to reduction of air density, the wind speed starts to decrease. Thus, the optimum operation height of the AWEGSs in the HAWEGS should meet both the maximum wind power density and high wind occurrence probability. From the NCEP/DOE reanalyses, optimal height and optimal wind power density for the yesr with three-month resultion were found. These optimum heights and the corresondig wind power densities and probabilities are given in the Table III.

TABLE III. OPTIMUM HEIGH AND CORRESPONDING WIND POWER DENSITY WITH 3-MONTH RESOLUTION FOR OCCURANCE PROBABILITIES EXCEED 50%, 68%, AND 95% FROM THE NCEP/DOE REANALYSES [5].

	Optimum Height (km)	**Wind power Density (KW/m^2)**	**Occurrence Probability (%)**
DJF	8	10	50
	8	10	68
	6	3	95
MAM	8	5	50
	8	3	68
	2	0.5	95
JJA	8	5	50
	8	2	68
	2	0.5	95
SON	10	10	50
	8	5	68
	4	0.5	95
Annual	8	5	50
	8	3	68
	2	2	95

HAWEGS PERFORMANCE

G. HAWEGS Production

The output power of HAWEGS with 3-month resolution was predicted and plotted in Fig. 11 using power curve of AWEGS.

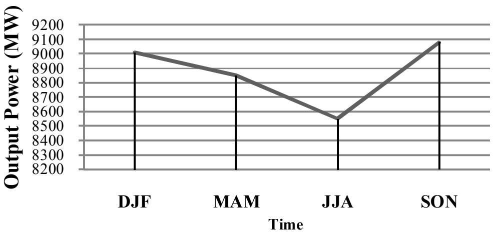


Figure 12. Predicted output power of HAWEGS with 3-month resolution.

Yearly output energy is computed 248000.000 GWh.

H. Monthly and Yearly Capacity Factor

The capacity factor can be easily computed using Eq. (1)

$$CF = \frac{1}{V_r^3}\int_{V_{cin}}^{V_r} v^3 f_w(v)dv + \int_{V_r}^{V_{co}} f_w(v)dv \qquad (1)$$

Where, V_{cin}, V_r and v_{co} are the cut in , rated and cut out wind speeds of used AWEGS. Capacity factors of the HAWEGS were computed for the altitudes at range of 7 km to up to 8 kilometers with 3-month resolution were charted in Fig. 12.

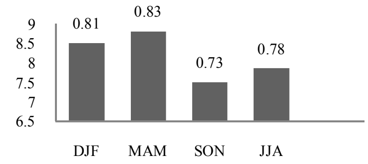


Figure 13. Capacity factore during each of the three-month.

The yearly capacity factor was obtained by finding the average capacity factors as 73%, which was four times bigger than capacity factor of covnetional ground-based wind turbines.

PROJECT COST

It is difficult to estimate exact cost of HAWEGS at early stage. However, approximate estimation of the cost based on cost of the used equipments can be presented. The cost estimates are based the cost of material and equipment on 2012, and condition of NREL guidelines [6]. Since the HAWEGS consists of several AWEGSs, once cost of the each AWEGS was estimated, a great share of HAWEGS cost could be found.

Starting from the AWEGS, the AWEGS constructed from a generation unit, and a transmission cable between the generation unit and the ground. Generation unit consists of several inflatable cylindrical wind turbines filled with helium gas. We assumed of $\$5/m^2$ for helium, and $\$10/kg$ for generation unit structure. In transmission cable, the costs for fiber and the cable were estimated \$3/m and \$8/m, respectively. At altitude of 8 km, the needed tether was 12km, thus, the cost of tether would be estimated. The cost of each foundation for the AWEGS was estimated about \$600. The complete cost was estimate, about a 2600\$ for each AWEGS with its foundation. It should be emphasized that, this is the cost for production of single AWEGS, by populate production of the AWEGSs for deployment of the HAWEGS, the cost would significantly be decrease. Due to nature of AWEGS which only was anchored to a small point on the ground, it will not occupy land. Thus the cost of land was not considered in the costing. Thus, the cost of the HAWEGS with three sections, and 2566 of AWEGSs for each section, was estimated about 24.64 M\$. The cost hydrogen production d storage equipment regard the output power of the HAWEGS was estimated about 0.3 M\$ which the project cost is shown in Fig.13.

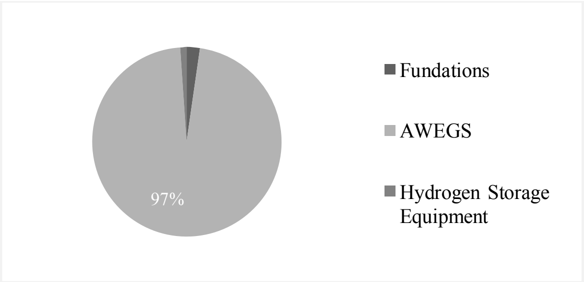


Figure 14. The Project cost chart

If the estimated power could be continuously produced in five years, cost of supplied energy is estimated as following. Annual Operating costs (AOC) includes Maintenance (M) and Replacement Costs (RC). AOC was mainly due to the hydrogen production which was estimated from recent hydrogen production systems. The M cost was derived from conventional wind turbine systems. Life time components were predicted to require replacement at five years. Replacement cost was estimated at 80% of the initial capital cost for the whole the HAWEGS. The M, and RC, for all the three sections were estimated at \$0.0102/kWh, \$0.0103/kWh, and \$0.0129/kWh, respectively. A Constant Charge (CC) of 0.0750/yr was considered. By using equation (2), cost of energy was calculated as \$0.014/kWh.

$$COE = \frac{CC \times ICC}{APP} + AOC \qquad (2)$$

However, by deployment of several HAWEGSs, lower electricity price can be obtained. Since the average cost of wind energy in the U.S. is approximately 0130\$/kWh, deployment of such HAWEGS can significantly reduces the cost of energy. Lower installation cost of the HAWEGS, fast deployment and reliable output energy would cause to reduction of the energy cost.

Furthermore, due to used lighter than air gas in structure of AWEGSs, the resulted bouncy force keeps it always in the air, preventing from falling of the HAWEGS. Thus, the HAWEGS are enough safe to employ in urban and populate areas. Moreover, to create a HAWEGS, permissible distance between AWEGSs is just few hundred meters result in small land consumption. Hence, the HAWEGS could be deployed also above the New York City to trap the vast dense layer of energy lies above it. Thus, the transmission system between the HAWEGS and this city significantly would reduce. Hence, the transmission loss and the cost would decrease, causing to a significant reduction of electricity price.

RISK MANAGEMENT

The HAWEGS faces to several risks such as lighting strikes, interface with commercial and private aircrafts, extreme wind conditions, bird storks, and sun degradation. Furthermore, deployment of the HAWEGS my change the general circulation patterns and has effects on global and local climates. The lighting strikes can easily be alleviated using lighting protection. A practical application of this protection is used for tethered Barry balloons in UK protected against 75–30 of storks [8]. The interface with commercial and private aircrafts can be solved by placing radars to monitor air traffic, and using visible lamps or sending electromagnetic signals as warning messages by a transmitter to the aircrafts. In case of wind gusts, and extreme wind conditions, the tether can be reeled around a drum, landing the HAWEGSs on a small land. Birds strokes can be alleviated by broadcasting sounds of the birds during danger, which can significantly deflected the bird flying path. This method is being currently used in the airport for prevention of flying of birds. Also, radar technology is able to identify approaching birds up to seven kilometers away, investigate their altitude, numbers, and wind direction to conclude if they are in danger of flying into the HAWES. In case of danger, the HAWES will automatically shut down and restart when the birds are passed. The dangers, due to the sun radiation, which cause to degradation of turbine, can be alleviated by covering the turbines surface with reflective materials, like foil, which can significantly reduce material degradation. Finally, to discuss the effects of the HAWEGS on the climate pattern, a similar approached which was presented in [6] was considered. Based on total sizes of AWEGSs, an area of $10000\ m^2$ per $k\mathrm{m}^3$was considered for th HAWEGS.A global climate model which comprises the atmosphere and the upper ocean was adapted, and performed at 3 deg latitude by 4.5 deg longitude resolution for 40 years. Simulation results were given in Table I. The results demonstrated reduction of surface temperatures by -$0.2C^0$, by 9.1%, and increasing sea ice cover, by to 17.2%. The total precipitation deceased by 19%, as were charted in Fig. 14. Due to global warming deployment of the HAWEGS can moderate the temperature trend of temperature as well as the resulted climate changes.

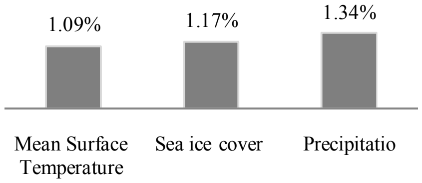


Figure 15. The The climate change due to deploymnet if the HAWES which were charactarectize with temprature, sea ice cover, and precipitation.

CONCLUSION AND PERSPECTIVE

The paper has presented feasibility study of a high altitude wind power generation station with rated power of 0.1TW above the Catskill Mountains, in New York State. For smooth electrical generation of the HAWEGS, a sectionalized configuration with three interconnected sections for it is presented. Modeling of every AWEGS and HAWGS is presented. A multi-stage procedure for feasibility study of the HAWEGS, which can be employed for other similar sites is proposed and followed. 27 years of wind data from the NCEP/DOE global reanalyses, over this region were analyzed, and presented as vertical profiles in 3-month resolution. Optimum height for operation of the AWEGSs in the HAWEGS was founded. It was shown that an annual production about 248.000 TWh in year with capacity factor of 86% by deployment of such HAWEGS in this region is achievable. The capacity factor of this power station is 4 times bigger than ground-based wind turbines. At the end, it is worthwhile mentioning that the current work is a preliminary study. Further works should be focused on technical experiments field. Climate model simulations were carried out which revealed a reduction in the earth surface temperature.

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APPENDIX

TABLE IV. CONSIDEREATIONS

Assumptions	Parameter	Near Term Assumption	Mid Term Assumption	Long Term Assumption
Electrolyzer	Size	1000 kg/day	1000 kg/day	1000 kg/day
	Electrolyzer, Capital Cost	$2.302.000	$1.220,000	$790.000
	Replacement Cost	$1.110.600	$576.000	$307.000
	Maintenance	$115.100	$61,000	$39.500
	Sizes to consider	6900 kW	6900 kW	6900 kW
	Lifetime	10 years	10 years	10 years
	Efficiency	73%	79%	85%
	Compressor Cost	$400.000	$500.000	$900.000
	Compressor Energy Requirement	10.09 kWh/kg	10.09 kWh/kg	10.09 kWh/kg
Hydrogen Storage	Size	12000 kg	12000 kg	12000 kg
	Capital Cost	$93.000	$40.000	$26.000
	Replacement Cost	$93.000	$40.000	$26.000
	Lifetime	20 years	20 years	20 years