NOVEL ELECTROSTATIC WIND ENERGY CONVERTER: AN OVERVIEW

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Abstract: The article discusses the historical development and embodiments of the concept of generating electricity from wind energy without the use of wind turbines, so called electrostatic bladeless generators or generators without moving parts. A simplified theory and the principles of operation of generators that use a motion of charged particles in an electric field occurring under the drag force of the wind are described. Two contemporary solutions utilising the principle that has reached an implementation stage, EWICON and Aerovoltaic^{TM}, are presented in detail.

Keywords: electrostatic wind energy converter, bladeless wind generator

1. Introduction

Wind energy is generally considered an environment- and climate-friendly form of energy with no fuel costs, no harmful emissions or hazardous waste. It has been exploited by people for thousands of years: initially mainly for transportation using sails to propel ships and later also in different kinds of windmills that would use mechanical energy for grinding grain, pumping water or crude oil. Since the 19th century it has been utilized also for production of electric energy. Nowadays wind energy is one of the fastest growing sectors of the energy industry and its distribution in the global energy production is expected to increase significantly in the nearest future.

Currently the main, mature, efficient and reliable method of producing electricity from wind is to use wind turbines, both in separate units and in large wind farms. Despite the advantages of conventional wind turbines, many of their shortcomings are also known. These are: noise, visual pollution and so called shadow flicker occurring when the sun passes behind rotors and they cast a shadow over nearby areas [1]. Additionally, turbines can work only below the cut-out speed over which power production is stopped to prevent excessive loading of

blades. Wind turbines are the cause of bird fatalities by direct contact with turbine rotors however – what is less known – they also cause massive bat fatalities due to barotrauma caused by the jump of air pressure occurring near moving turbine rotors [2].

The increasing world demand for sustainable energy sources forces the development of the known technologies to increase their efficiency and lower the costs of maintenance and production but also search for new technologies that would be both efficient and free from disadvantages.

The above mentioned drawbacks of wind turbines result mainly from the fact that wind energy is converted into electrical energy through mechanical energy of rotating blades with shafts, bearings and gears. Elimination of this intermediate stage of energy conversion can drastically decrease the costs of producing and maintaining the energy conversion devices and change the way in which the wind energy is used.

The conversion of mechanical energy into electrical energy without rotational movement is possible and has been a subject of interest for years. Such direct conversion might take advantage of the fact that the electric current is actually a movement of charged particles and this movement can be forced by mechanical forces. An early example of such a conversion device is the so called Kelvin's Thunderstorm, a high-voltage generator without moving parts powered by the energy of falling charged droplets [3]. A similar approach can be found in the very recent research of harvesting electrostatic energy of jumping-droplets [4]. In these two examples the movement of charged droplets occurs in the gravitational field.

However, more effective and flexible energy conversion could be achieved by charged particle movement in the electric field which direction and shape can be formed much easily. Devices employing this method were developed and patented in the 1930s and 1940s. An electrostatic generator, *i.e.* a device for producing difference of electrostatic potentials and the electric current, disclosed by Simon [5] who employed gaseous carriers such as gas ions, fine droplets or solid particles suspended in gas transported or propelled up in dielectric tubes against the electric field by circulation forced by fans. A corona discharge was suggested for charging the particles. Simons's concept was based on earlier versions of electrostatic generators in which the electric carriers were transported on dielectric discs or belts. This idea was developed in the subsequent years by Alvin Marks [6, 7] who formulated the theory and proposed many modifications of generators to increase the energy conversion efficiency [8–10]. Generally, he reduced the dimensions of the device suggesting to use capillaries instead of tubes for the gas flow and properly shaped nozzles to increase the speed of gas. Additionally he proposed assembling these small elements into arrays and super arrays of many items to achieve the required power outcome.

A concept of employing the wind to force the charged aerosol flow and hence produce the electric current emerged in the 1970s. It was shown theoretically [10]

that under reasonable assumptions about the wind speed the electric power of $1\,kW$ could be achieved from $1\,m^2$ of the surface subjected to wind. That was why the idea soon began to grow mainly in the US, supported by governmental grants. The so called Wind/Electric Power Charged Aerosol Generator was designed and investigated by Marks [11] and a similar Electrofluid Wind Generator – by Minardi [12, 13]. In their theoretical and experimental works, water was investigated as the working liquid and the shape, dimensions and hydraulic and electrical parameters of the devices such as applied pressure and voltage was optimized. Subsequently, the concept feasibility was demonstrated by showing experimentally that the net electric power output can exceed the input sum of the hydraulic power required to pump water and the electric power required to supply the system. Conceptual, scaled-up models of generators 85 m high and 400 m long to achieve required 2.25 MW of electrical energy were designed.

Although it was proven that it was possible to extract energy from wind using charged aerosol electrostatic generators, the efficiency of the transduction process was too low to be applied in practically accepted solutions. It was merely due to problems with the too small efficacy of charging aerosol or particles. The concept of producing electricity from wind devices based on a charged particle flow seemed abandoned for years, however, in the last decade a renewed interest in electricity generators without moving parts, the so called bladeless or vane-less technologies, has been observed and progress has been seen both in the EU and the US. The new ideas and solutions developed lately are presented in the next chapters.

2. Concept of electrostatic wind energy generators

The basic idea behind bladeless electrostatic wind driven energy generators is in the fact that electrical charges moving against the forces of the electric field gain potential energy that can be next utilized practically. When it is the wind that drags the charges, the kinetic energy of wind is converted into electric energy. This can be compared to a situation where a stone is rolled up the hillside and thus gains the gravitational potential energy, which can next perform useful work.

The general concept of operation of an electrostatic wind energy generator is presented in Figure 1. The generator comprises a particle emitter that generates and electrically charges the particles, and a particle collector. The direction of the force exerted by the electric field between the emitter and collector on charged particles is opposed to the wind that drags the particles against this field and performs work. When the particle reaches the collector, the energy it has gained can be utilized in the form of the electric current flowing through the electric load. Continuing the comparison with the stone in the gravitational field one can say that the energy of the stone that has reached the top of the hill can be utilized for useful work, when the stone is rolling down on the opposite side of the hill.
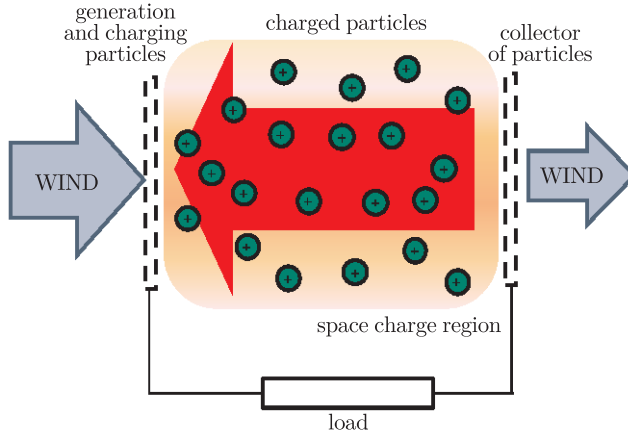
Figure 1. Concept of electrostatic wind energy generator operation

Different embodiments of the electrostatic wind energy generators are proposed in the literature. They differ by the type of particles, methods of particle generation and charging, the shape and parameters of the electric field and the type of particle collection. The particles may be ions, bubbles or droplets of a liquid such as oil, ethanol or water and may include solid particles inside. Typically and preferably water or water solutions are used as liquids. The production of particles and charging them may be separate or combined processes. For example, the droplets may be generated by passing liquids under water or steam pressure through capillaries [11]. Ink-jet technology with piezoelectric vibration has been suggested in newer solutions [14, 15]. Particles may be charged by diffusion of ions produced in a corona discharge [12] or by induction in a suitably shaped electric field [10, 11]. Other kind of devices like micro-electro-mechanical structures (MEMS) or dielectric barrier discharge (DBD) suggested in [15] can be applied for ion production. Metal thin wires, rings or cylinders can be used to shape electric fields. Specially shaped nozzles can be used to modify the gas flow velocity. Different kinds of metal screens or grids were suggested in the very first solutions for the collector of particles. However, quite early it became obvious that this part of the system was not a necessary component because the earth could act as a collector. This solution, which may drastically simplify the design of the generator and offer lower costs of production and maintenance, has been presented in the report [11] and patents [16, 17]. In such case, the load on which the electric power is deposited must be grounded.

Due to the particle production methods, a single element of an electrostatic wind energy generator has small transverse dimensions typically smaller than millimeters, the electric current is of the order μA and the power of mW is expected. To obtain power that could be compared with the power produced by conventional turbines, the single element should be multiplied to achieve the transverse surface similar to the conventional turbines. Such structures have been proposed in the form of long fences [16, 17] or high towers [13].
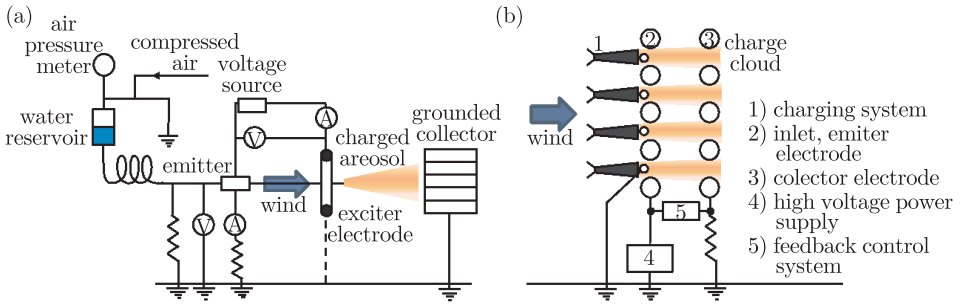
Figure 2. Examples of early concept of electrostatic wind energy generators based on figures from (a) [11] and (b) [13]
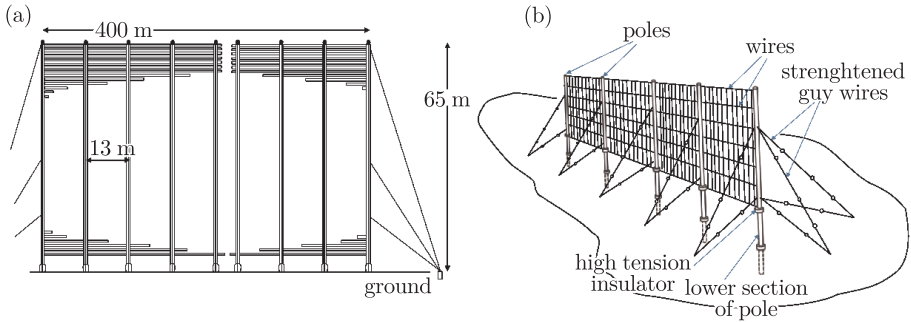

Figure 3. Scaled conceptual electrostatic wind energy generator designs, (a) [13], (b) [16]

Figure 2 shows examples of electrostatic wind energy generators, developed and tested theoretically and experimentally and Figure 3 shows how the concept has been predicted to be used in practical devices.

3. Theory of electrostatic wind energy generators

With the development of charged aerosol electrostatic generators also a theory explaining their operation was formulated. The main goal of this theory was to find optimum conditions for the energy conversion process. Much of the work was done by Marks who presented the theory in papers and patents [6, 7, 10]. He applied a thermodynamic approach with Poisson's equation. He found that the effectiveness of power conversion depended to a large extent on the ratio of particle radius to the electric charge deposited on a particle. Marks performed a parametric study to find the optimum ratio for different kinds of gases, gas velocities, temperatures and other parameters. He also tried to find means by which the optimum ratio could be achieved. The theory was simplified to a 1D case, had many limitations and was confined to operational conditions that were not very suitable for wind electrostatic generators, i.e. higher gas temperature, velocity and electric potentials.

A simplified but highly useful theory that relates directly to electrostatic wind energy generators can be found in the works of the Delft University of Technology team and it is presented here following their works [18, 19].

As is shown schematically in Figure 4 different forces act for the charged particle or droplet in the electrostatic wind energy generator such as presented in Figure 1. These forces are: $\boldsymbol{F}_e$ – the electrostatic force exerted by the electric field between the emitter and the collector, $\boldsymbol{F}_d$ – the wind drag force, $\boldsymbol{F}_g$ – the gravity force and $\boldsymbol{F}_b$ – the buoyancy. Taking into account that the particle is surrounded by other charged particles, an additional electrostatic force being the sum of electric interactions between the particles should be added. This force coming out from the space charge is marked as $\boldsymbol{F}_s$.
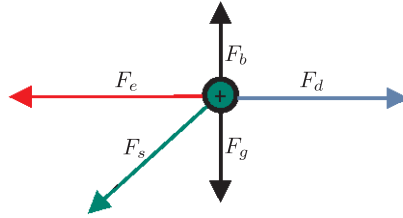

Figure 4. Forces acting on charged particle in electrostatic wind energy generator

The values of these forces acting on particle i can be found from the following formulas:

$$\boldsymbol{F}_e = q_i \boldsymbol{E} \tag{1}$$

$$\boldsymbol{F}_g = m_i \boldsymbol{g} \tag{2}$$

$$\boldsymbol{F}_b = -\rho_g V_i \boldsymbol{g} \tag{3}$$

$$\boldsymbol{F}_d = 2\pi \eta_g d_i (\boldsymbol{u}_w - \boldsymbol{u}_i)/C_c \tag{4}$$

$$\boldsymbol{F}_s = \frac{1}{4\pi\varepsilon_0} q_i \sum_j \frac{q_j}{r_{ij}^3} \boldsymbol{r}_{ij} \tag{5}$$

where q_i, m_i, V_i, and d_i are the particle charge, mass, volume and diameter, respectively, ρ_g and η_g are the gas density and dynamic viscosity, respectively, $\boldsymbol{u}_w$ and $\boldsymbol{u}_i$ are the wind and particle velocity, respectively, ε_0 is the electric permittivity of vacuum, $\boldsymbol{g}$ is the acceleration of gravity, $\boldsymbol{r}_{ij}$ is the vector connecting particles i and j, with r_{ij} being its module, C_c is the corrector factor that can be estimated as 1 for typical conditions. Applying (4) it is assumed that the gas velocity is small enough for the flow to be laminar. Summation in (5) is done over all particles different that i.

In a first approximation it is reasonable to assume that all the values except for the particle velocity $\boldsymbol{u}_i$ and relative position vectors $\boldsymbol{r}_{ij}$ are constant. Solving Equations (1)–(5) numerically in the 3D space for a given shape of the electric field and the assumed number of particles whose parameters, initial position and velocity are known, it is possible to find trajectories of particles. In consequence it is also possible to determine for which parameters the particle can reach the collector. It is an important result because the higher fraction of particles reaches

the collector, the higher the efficiency of the energy conversion process. Under optimum conditions, all particles should reach the collector. The calculations allow also estimating the work performed by the wind on the particle, which is equal to the linear integral of the component of the resultant force parallel to the particle path over this path. In more detailed calculations it is necessary to take into account the changes of the particle dimensions and mass resulting from evaporation, which depends on the humidity and temperature, and the fact that particles may differ in size, mass and charge.

From Equation (4) it is seen that the drag force increases with the particle dimensions, thus, for the same charge the larger particles can overcome the electric potential difference more easily. An additional feature of the drag force is that it decreases when the particle velocity increases and vanishes when $\boldsymbol{u}_i = \boldsymbol{u}_w$. Since this moment the wind does not perform work on the particle. It is an unfavorable effect that should be avoided in a practical design of a generator. To overcome this problem the electric field intensity has to be adjusted to the expected wind speed range taking into account the properties of the particles and the gas. It is particularly the particle diameter range that can be determined from these constrains. For reasonable assumptions about the wind speed it is found in [18] that for water particles and air the particle diameter should be in the range of 0.1 to $100\,\mu$m.

Assuming that all charged particles reach the collector, the electric current that flows between the emitter and collector I can be found from

$$I = \frac{q_i}{m_i}\frac{dM}{dt} \tag{6}$$

where dM/dt is the mass flow rate of the liquid forming the particles. This means that for a constant mass flow rate the current increases with the charge per mass ratio q_i/m_i. However, this important parameter cannot be increased arbitrarily because the maximum charge that can be stored on the particle cannot exceed the Rayleigh limit, which depends on the particle diameter and surface tension [20]. When the limit is exceeded the particle drops out into a smaller one, which is an unfavorable effect. In practice the charge per mass ratio should be large but not too close to the Rayleigh limit because evaporation processes can lead to decreasing the particle diameter and exceeding the Rayleigh limit.

The theory which is presented here gives an insight into basic phenomena occurring in electrostatic wind energy generators. A more detailed description requires solving a set of partial differential equations including the balances of mass, momentum and energy together with Poisson's equations for a specific experimental set-up. Such calculations for an electrogasdynamic power converter can be found in [21], where there is also a literature survey on CFD simulation of charged particles in an electrohydrodynamic flow.

4. Contemporary design of electrostatic wind energy generators

Understanding the physical phenomena and the resulting constrictions as well as employing new methods of production of charged droplets with the desirable features, and the growing interest in renewable energy revived the concept of electrohydrodynamic wind power generators in the 2000s. In 2015 at least two teams have passed the stage of research and come to the stage of practical implementation. These are: the Dutch group from the Delft University of Technology, which has designed and developed a generator named EWICON (Electrostatic WInd Energy Converter) and the American company Accio Energy, which has named their invention the Aerovoltaic^{TM} generator.

The Delft University of Technology group started working on the EWICON concept in 2003 [22] and has published several scientific papers presenting the development of the concept since that time. A summary of the research can be found in [18, 19]. The EWICON system is the one where the earth acts as the particle collector. Such a solution leads to a simpler design and is more economical but requires good electrical insulation and using environmentally benign liquids. Different methods of particle generation and charging have been tested by the authors of the EWICON system, and three of them have been chosen as most promising for future research: High-Pressure Monodisperse Spraying (HPMS), Electrohydrodynamic Atomisation (EHDA) and electrohydrodynamic atomization with Self-Adjusting Nozzles (SAN).

In the HPMS method, the liquid is ejected under the pressure of 10 to 15 MPa through micron-size diameter capillaries producing droplets of the same diameter, which are then charged by induction using a ring electrode kept on a high electric potential. By changing the potential it is possible to control the charge deposited on a droplet. A drawback of this method is that it requires relatively high energy to force the liquid flow.

The EHDA method also known as EHD spraying takes advantage of the fact that the liquid flowing from a capillary maintained at a high electric potential can break up into charged droplets [23]. This spraying process has different modes depending on the electric field, the nozzle geometry, the fluid flow rate and fluid properties such as density, viscosity, surface tension and conductivity [24]. In the so called cone-jet mode, where Taylor cones are created, monodispersity and high charge on a droplet can be obtained, which are desirable features. A shortcoming of this method is that it is difficult to obtain a situation when all the particles reach the collector because they are attracted by the inducing electrodes. To minimize this effect the authors have performed both theoretical and experimental optimization of the electrode configuration. They have found that adding an additional (steering) electrode can change the electric field in the desired way. Figure 5 presents plots of the z-component of the electric field for two cases: without and with the steering electrode. They are obtained by solving Poisson's equation in 3D space corresponding to the experimental

geometry consisting of a nozzle and two rod electrodes kept on a high potential. The blue region in the close vicinity of the nozzle is unfavorable. It is seen in Figure 5b how adding the steering electrode decreases this region. The blue region far from the nozzle (upward to the wind) does not have any such unfavorable influence.
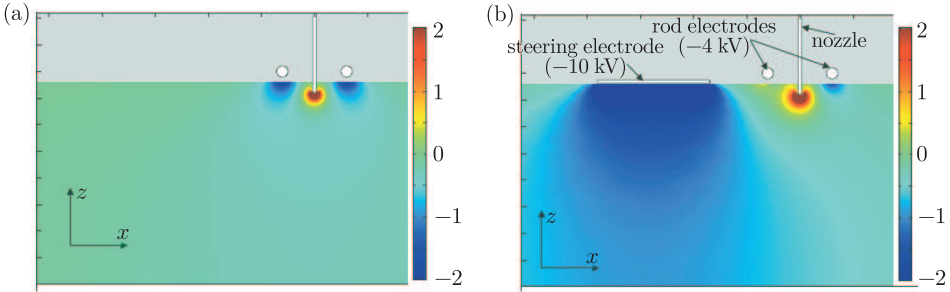

Figure 5. z-component of electric field in EWICON system (a) without steering electrode; (b) with steering electrode. The scale is in (V/m)

Despite the optimization it has not been possible to obtain experimentally a situation when all the particles would reach the collector. Additionally the output power does not rise linearly with the number of nozzles.

The SAN method is a modification of EDHA with a much simpler structure. Instead of a row of nozzles, a strip of porous material is used to distribute the liquid. The Taylor cones are created in the electric field and its size and number tend to self-adjust to the electric field, amount of liquid and the wind speed. These cones are the source of charged droplets.

Different electrode configurations and liquids have been tested. The results presented for water as the working liquid presented in a recent research [19] can be summarized as follows. The electric currents obtained for one nozzle for the wind speed of $10\,\text{m/s}$ are $0.1\,\mu\text{A}$, $0.2\,\mu\text{A}$ and $0.02\,\mu\text{A}$ for the HTMP, EHDA and SAN methods, respectively. The scaled power densities for the same conditions are $2.1\,\text{W/m}^2$, $2.3\,\text{W/m}^2$, and $1.3\,\text{W/m}^2$ for HTMP, EHDA and SAN, respectively. It is also shown that the output power density increases as third power of the wind speed. The efficiency of energy conversion, which is the ratio of the obtained power taking into account the effective wind surface area to the net input power, is estimated as 0.11, 6.9 and 2.7 for HTMP, EHDA and SAN, respectively. When relating to the theoretically determined maximum wind power that can be obtained, the so called Betz limit, these efficiencies are 0.3%, 2.3% and 1.3%. It is worth noting that the efficiencies obtained for liquids with smaller surface tension such as a mixture of water and ethanol are much higher, however such mixtures cannot be used, if the device is going to work in the open space.

Although the results may seem not too impressive it is important that the feasibility of a bladeless electrostatic wind converter working with water as the working liquid is practically demonstrated and the working prototype can

be observed in front of the Faculty of Electrical Engineering, Mathematics and Computer Science at the Delft University of Technology. What is more, recently a project named the Dutch Wind Wheel seen as a sustainable future icon has been announced by Dutch Windwheel Corp, a consortium of Rotterdam-based companies [25]. The EWICON system has been chosen from among other state-of-the-art sustainable concepts to be implemented as part of a 174-meter-high structure comprising two huge three dimensional rings that is going to be a new landmark of the city.

The second team developing the electrostatic wind energy generators, Accio Energy [26], a company led by Dawn White does not present their results in scientific articles but in patents, *e.g.* [15, 27] and reports prepared for governmental agencies supporting the work such as [28] that was done in cooperation with Boeing. The idea behind their Aerovoltaic^{TM} systems is to prepare modular panels, producing several kW each, that can be used in a similar way like a photovoltaic panel, *i.e.* on roofs, walls, in gardens, that can be configured in a flexible way. The company claims that they have obtained the net output power of almost $10\,W/m^2$ and predicts to improve it in the nearest future [28], however, they do not reveal how they have achieved such results.

White et al. performed both theoretical and experimental tests of different type of nozzles including pintle nozzles, capillary ending shapes, diffuser and airfoil shapes that increase the gas flow speed. With 3D multiphysics simulations performed using Fluent^{TM} and elements fabricated by Boeing, using stereolithography and laser sintering techniques, they have been able to optimize the generator elements to obtain the highest output power density, so far. It has been possible also due to achieving a high system operating voltage which is above $200\,kV$, whereas in the EWICON system it was about $10–50\,kV$.

In their solutions, Accio takes into account also the space charge influence on the whole system (Equation (5)) whose influence may prevail over the external electric field force and they have patented methods of neutralizing this space charge when its influence is unfavorable. They have also patented the way of controlling the whole system by monitoring the ambient conditions such as the wind speed and direction, temperature and humidity to adjust the parameters of the generator such as the electric potential, liquid flow rate, droplet size and charge to achieve the maximum energy conversion efficiency in given conditions.

With their accomplishments, they forecast to exceed 100 W/m². At the present time they are testing their modules in an open field in Dexter and they are prepared to demonstrate them working offshore.

5. Conclusions

Extracting electric energy from wind using a technology without moving parts has been a temptation for decades. The challenges have stemmed from the fact that a solution requires a multiphysic approach and mastering various

fields of technology, such as effective production of charged particles, a two-phase flow and proper handling of an electric field, which have to be supported by numerical simulations. When the feasibility of the electrostatic wind energy conversion solution had been proven, big companies such as General Electric [14] and Boeing [28] joined the research. Theoretical considerations indicate that there are big possibilities to improve the results obtained so far. Thus, the vision of the future, in which electricity is produced from wind energy by modular panels in a quiet way without turbines is conceivable.

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