Analysis of the Economic Viability of Ion Power Generation

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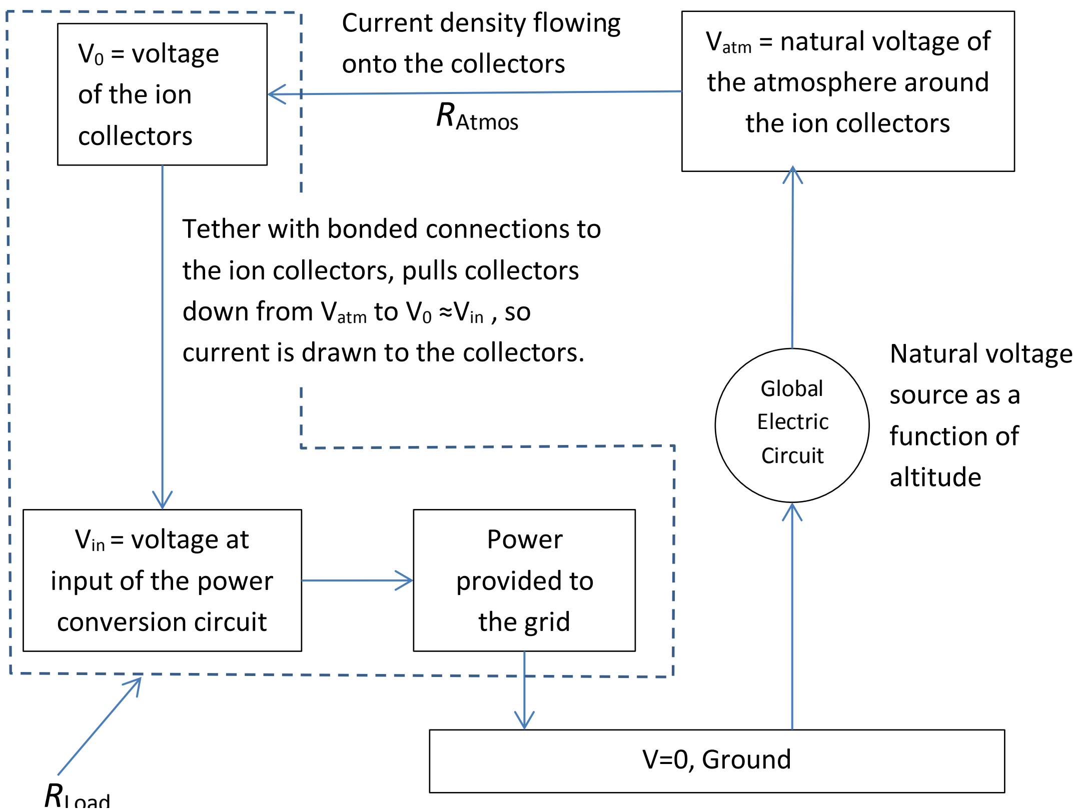
Ion Power works as shown in the following diagram. The voltage source behind this power system is the Earth's global electric circuit. The Ion Collectors are positioned in the atmosphere to couple with the high voltage, pulling current to a lower voltage where it does electrical work through the electrical power grid. This report will first discuss how it works, then how it can be scaled up to industrial application, and then the economic viability of this power source.



How Ion Power Works

The Ion Power Group has performed tests at its facility in north Florida, successfully demonstrating the critical function of the technology application using their patented, carbon-based ion collector material, thereby achieving Technology Readiness Level 3 (TRL-3). In some of these tests, 400 ion collectors were distributed on a square grid 91.44 m (300 ft) on a side along cables stretched between poles at 39.6 m

(130 ft) above the surface. This means they were about *d* = 0.91 m (3 ft) apart. The collectors were made of the patented carbon material with a texture that enhances electrical contact with the atmosphere. Each collector was a strip of the carbon material *L* = 30.48 (12 in) long and 1.59 mm (1/16 in) wide (thickness not reported) for a two-sided surface area of *A*=9.69 cm^2. During "peak ion conditions" (a storm directly overhead), 41,200 V potential was measured on the cable descending from these ion collectors. The power collection circuit was connected and set to pull the voltage down to $V_{\text{in}} =$ 1000 V so it would pull current from the ion collectors. The potential difference between the ion collectors and the surrounding atmosphere was therefore $V_0 =$ (41,200 – 1000) = 40,200 V. This resulted in $I =$ 30 mA current, so $R_{\text{Load}} =$ 1000 V / 30 mA = 33.3 kΩ and the usable collected power was 1000V x 30 mA = 30 W. Thus, each collector produced on average $I_0 =$ 75 µA of current and 75 mW usable power. Additional energy of 40,200 V x 30 mA = 1.206 kW was dissipated in the atmosphere and/or on the collector surface as heat due to the finite conductivity of the atmosphere, where $R_{\text{Atmos}} =$ 40,200 V / 30 mA = 1.34 MΩ. Future work could adjust the voltages to optimize usable power collected at the ground. A crude estimate (using the maximum power transfer theorem by assuming ion collector performance is linear) says that setting $R_{\text{Load}} = R_{\text{Atmos}} = 1.34\ \text{M}\Omega$ would produce maximum usable power. However, an actual calculation depends on details of the scaling relationships, discussed below.

Does It Simply Collect Ions?

The first question to investigate is whether the method of generating this power is simply by pulling ions from the surrounding air. To help answer this, some simplifications will be made. The ion collectors are sufficiently close together that their electric fields probably affected each other in the region of interest. They would draw current away from each other reducing their individual performance, and thus they should perform individually better if alone. What follows therefore is an underestimate of their individual performance. Let us draw a sphere around an ion collector at $r_1 = 10\ L = 3.048\ \text{m}$ so we can treat it as a point source or as a small sphere. Then at that distance,

$$E_1 = \frac{V_0}{r_1} = \frac{40{,}200\ V}{3.048\ \text{m}} = 13.2\ \text{kV/m}$$

The atmospheric electrical conductivity varies with altitude, storm conditions, and other factors. Near the ground, the voltage is known to increase linearly with height *h* above the surface, $V(h) \approx \chi h$, which is the condition when the electric field is constant and there is negligible net charge in the air. Typical clear air values range from 10^{-13} mho/m at ground level to 10^{-7} mho/m at 80 km altitude.[1] During a thunderstorm it may be different but very few studies have been made so the data are inadequate. To produce the observed current at the observed voltage during storm conditions by simply drawing in surrounding ions, the conductivity would need to have been

$$\sigma = \frac{J}{E} = \frac{I_0}{4\pi {r_0}^2}\frac{r_0}{V_0} = \frac{(75\ \ \mu\text{A})}{4\pi(3.048\ \text{m})(40{,}200\ V)} = 4.9 \times 10^{-11}\ \text{mho/m}$$

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[1] Siingh, Devendraa, V. Gopalakrishnan, R. P. Singh, A. K. Kamra, Shubha Singh, Vimlesh Pant, R. Singh, and A. K. Singh. "The atmospheric global electric circuit: an overview." *Atmospheric Research* 84, no. 2 (2007): 91-110.

which is about 500 times the typical value near the ground. We now investigate whether this is a reasonable value.

There is little published information on the conductivity of air beneath or inside thunderstorms. In a 2012 review, Nicoll[2] writes that theoretical calculations have put the conductivity inside thunderstorms from <0.05 to 0.1 of its clear air value to as high as 20 times greater than in clear air. A few measurements were made inside thunderstorms finding *possibly* 10 to 100 times the clear air values, but with significant questions about the measurement accuracy or validity. (Note that these measurements were far above the ground, suggesting the conductivity at 130 ft. cannot possibly be 500 times clear air values.) Other measurements in the bases of developing thunderstorms found the conductivities were always less than clear air value and typically 1/6th to 1/10th the clear air values for the same altitude. Considering these results, it seems unlikely the conductivity near the ground during the ion power tests was high enough to explain the observed current and power, so other factors besides conductivity must be the cause. Therefore, the system is not simply pulling in ions from the surrounding air. Besides, we note that if this is all it were doing, then simple metal conductors could be just as effective since they could create the exact same voltage and electric field around them. We conclude in answer to our first question that the system does not simply collect ions from the surrounding atmosphere. Something else is happening that actually increases conductivity of the air around the ion collectors.

Does It Ionize the Surrounding Volume of Air?

Since the ion collectors must be increasing conductivity in the air somehow in order to get so much current for so little voltage, the second question is whether the electric field is ionizing the volume of air around the collectors, creating more ions and free electrons to increase overall conductivity. This could be the mechanism that explains performance if the electric field is high enough to induce ionization. The electric field that causes dielectric breakdown of air is about 3 MV/m. As calculated above, the electric field about 10*L* from an ion collector will be only about 1.32 kV/m, so it would need to be more than a factor of 2000 times larger to produce ionization over such a large volume. Looking over smaller volumes the point charge approximation becomes increasingly inaccurate. Therefore we must use a thin cylinder approximation to get a better estimate over those smaller spatial scales. Treating the collector as a cylinder segment of length *L* and radius r_2 such that the cylinder has the same exterior surface area as an actual (2-sided) ion collector, *A*=9.69 cm^2. This yields r_2= 0.505 mm. Since $r_2 << L$, we can validly treat it as a line charge so the electric field at a distance *z* perpendicularly away from the centerline of the line segment is

$$E = \frac{Q_{\text{collector}}}{2\,\pi\epsilon_0 z\sqrt{L^2 + 4z^2}}$$

where $Q_{\text{collector}} = \rho_L L$ is the total charge on one ion collector, and ρ_L is the equivalent line charge density. The voltage on the ion collector is therefore,

[2] Nicoll, K.A. (2012) Measurements of atmospheric electricity aloft. Surveys in Geophysics, 33 (5). pp. 991-1057.

$$V_0 = \int_\infty^{r_2} \vec{E} \cdot \mathrm{d}\vec{s} = \int_\infty^{r_2} \frac{-Q_{\text{collector}}}{2\,\pi\epsilon_0 z\sqrt{L^2 + 4z^2}} \mathrm{d}z$$

$$Q_{\text{collector}} = 2\,\pi\epsilon_0 V_0 \left[\int_{r_2}^{\infty} \frac{\mathrm{d}z}{z\sqrt{L^2 + 4z^2}}\right]^{-1} = 374\ \mathrm{nC}$$

Using this and setting the breakdown limit at $E > 3\ \mathrm{MV/m}$, we can now calculate $z < 7.4\ \mathrm{mm}$ for the region of electrical breakdown (ionization) around the collector. This is about 4.6 times the width of the ion collector, so the line charge approximation is adequate. This tells us that any conductor at this voltage with these dimensions – not just the patented carbon material – will initially ionize that volume of air around it, enabling that volume of air to become a good conductor. Furthermore, once that space is ionized, the current flowing out from it will ionize an even larger volume where the electric field is inadequate to initiate ionization by itself. However, the rate-limiting physics seem to be in the boundary layer where the texture of the patented material dominates. Therefore, the new material should produce much higher power than a non-textured material, as discussed below.

Does It Ionize on Larger Surfaces?

We just saw that thin strips with these dimensions at this voltage can ionize a volume of air regardless of its material. The third question is whether this new material can ionize air when it is in other geometries such as large spheres (the collector material coating the surface of an aerostat) where the radius of curvature would be so large that other materials would not be able to ionize the air. For a sphere, the electric field will be $E = V_0/r$, so for $V_0 = 40{,}200$ and an ionization limit of E > 3 MV, the ionizing region will be r < 1.3 cm for any collector regardless of the material. This is a very small radius and would be the maximum size of an aerostat to create a current at this voltage. Aerostats of only 1.3 cm diameter would not be very practical. However, the patented carbon material has microstructural texture with much smaller radii of curvature $r \sim 0.03\ \mu\mathrm{m}$ (roughly scaled from Figure 2) at the tips of the protrusions, so ionizing electric fields will occur in the thin boundary layer across the surface of this material even when the collector voltage is as low as

$$V_0 \sim (3\ \mathrm{MV/m})(0.03\ \mu\mathrm{m}) \sim 0.1\ \mathrm{V}$$

which is remarkably small. Since we showed that a sphere of this radius at $V_0 = 40{,}200\ \mathrm{V}$ will ionize air to a distance of 1.3 cm, we conclude that an ionized

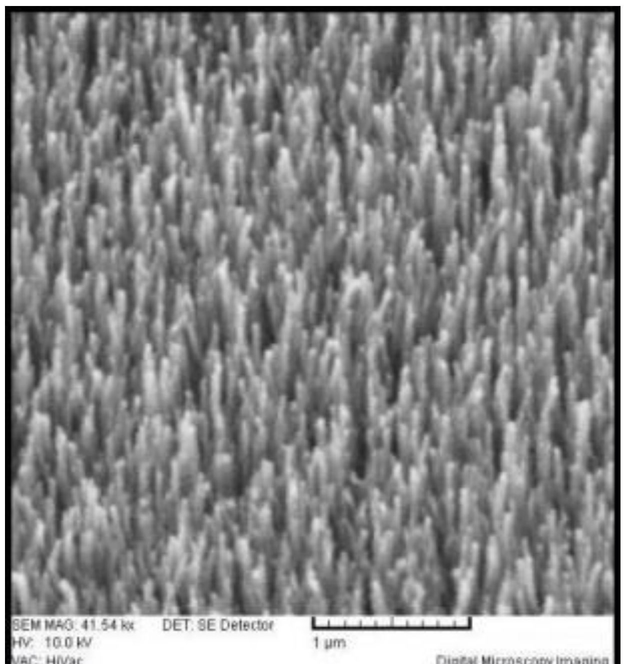


Figure 2. Scanning Electron Microscope image of graphite fiber ion collector surface showing the extreme surface area consisting of a "forest" of pins on the order of 1/10 micron diameter.

boundary layer of greater than 1.3 cm thickness will form all across the surface of the collector, regardless of its macroscopic geometry. As stated above, once ionization is initiated, the ionized volume will grow into the surrounding regions where the electric field is smaller, so a much greater volume of ionization may result. The effects are the same as before, resulting in a net emission of electrons into the surrounding air and the collection of useful power on the ground. Again, the rate limiting physics are difficult to estimate from first principles.

Rate Limiting Physics

Ionization around the collector will have the following effects. First, we assume the sky above the collector is positively charged so the ion collector is negatively charged relative to the surrounding air. In that case, all the positive ions created in that volume around the collector will be attracted to the collector where they will touch its surface and obtain an electron through the conductivity of the collector through its tether back to ground. This will neutralize the ion back to being a free air molecule, so it will diffuse randomly away from the collector's surface. Meanwhile, the electrons that were liberated in the same ionization volume will be driven away by the collector's negative electric field. This will create excess negative charge around the ion collector and a negative current density flowing away from the collector. The conductivity in the surrounding space will be correspondingly increased by the concentration of free electrons, and since they are being pushed beyond the ionization region they will increase the conductivity over a much larger volume of space. As the charge density moves away from the collector it spreads out as $1/r^2$, so the conductivity $\sigma(r)$ decreases correspondingly but the surface area through which this current density flows increases as r^2, so the total current is conserved as a function of *r.* This results in some steady state distribution of space charge, electric fields, and current densities in the volume around the ion collector, all vanishing toward infinite distance.

Unfortunately, predicting generated power requires knowledge of the current flowing through the system, which we can only obtain experimentally because the rate-limiting physics in the boundary layer is complicated for a number of reasons. First, ionization happens at some physical rate as a function of the air density, electric field, and concentrations of free ions and electrons. Second, positive ions will crowd toward the collector as a driven-diffusion process limited by molecular kinetics, and after being neutralized they will be released from the surface of the collector and move away in a random diffusion process, so this should result in some increase in air density and pressure at the surface of the collector. That pressure will tend to push both ions and molecules away from the collector. Third, the current density in the air produces heat, and that increases air pressure but lowers air density near the collector. The resulting temperature depends not only on generation of heat by this current density but also on conduction of heat away from that region through both the air and the collector, on convection of the air around the collector, on radiation of heat by the gas to the surrounding gas and to the collector, and by advection of the air (external wind) transporting heated air away. Fourth, the rate that ions are neutralized on the surface of the collector depends on molecular kinetics plus the microstructural surface texture of the collector and the complicated electric fields at the length scale of that texture and the conductivity of the collector material. Considering these complexities, it is necessary to measure the effects experimentally in the lab.

There seem to be two main benefits of the new material. First, it can ionize the air in any geometry even for extremely small atmospheric voltages, enabling large-scale collectors and enabling collection in low voltage conditions (clear air), whereas other materials can only work in small applications (e.g. thin strips) when the atmospheric voltage is lower. The ionization voltage is so low that this material can always generate power, although the power will still scale with voltage. Second, even when other materials can ionize the air, such as in disturbed weather or when small-scale collectors (such as thin strips) are being used, the new material should produce much higher current flow and much higher generated power, which can be verified experimentally. This second point is stated as likelihood rather than a known fact because it is not clear what the rate-limiting physics is in the boundary layer of the ion collectors. However, we have a pretty good idea that the rate-limiting problems are addressed by the microstructure of the new material. The new material provides vastly more surface area for ions to touch and receive an electron. Figure 2 shows approximately 70 needles per square micron, with average height of 0.4 micron and radius of 0.03 micron, so the material has about 6.3 times as much surface area as a non-textured surface. This analysis suggests that [one portion of] the rate limiting physics is proportional to surface area multiplied by Electric Field, so for a sphere of radius R_0 in voltage V_0 the power should scale as ${R_0}^2 \times (V_0/R_0) = R_0 V_0$.

Simple Math Model

To illustrate the behavior of the system just outside of where the complexities of ionization occur, we again adopt the simple model that we are far enough away from the collectors to treat them as point charges or small spheres. We use the sphere radius $R_0 = 8.78\ \mathrm{mm}$ that provides the same surface area as the tested ion collectors. We will also assume that this is far enough away that thermal motion of ions dominates over electrically induced motion, an assumption we will show to be correct, below. The electric flux density through a closed surface equals the enclosed charge, so by the Leibniz rule the incremental change in electric field moving radially outward is related to charge density in the atmosphere around the collector:

$$\oiint_{\text{at } r} \vec{D} \cdot \mathrm{d}\vec{A} = 4\pi\epsilon_0 r^2 E(r) = \iint_0^r \rho(r')dv' + Q_{\text{collector}}$$

$$4\pi\epsilon_0 \frac{\partial}{\partial r}\left(r^2 E(r)\right) = 4\pi r^2 \rho(r)$$

Non-dimensionalizing this equation with $x = r/R_0$, $\mathcal{E} = (R_0/V_0)E$, and $p = \left({R_0}^2/\epsilon_0/V_0\right)\rho$, where R_0 is the radius of a collecting sphere, and V_0 is the voltage determined by ground circuitry for that sphere relative to its surrounding atmosphere, and ϵ_0 is the permittivity of free space,

$$\frac{\partial}{\partial x}\left(x^2 \mathcal{E}(x)\right) = x^2 p(x)$$

Another relationship between E and ρ is obtained by the current density relationship, where the conductivity σ of the atmosphere is modified by the presence of free charge. In plasma physics, this relationship is used,

$$\sigma = \frac{n_e e^2}{m_e \nu_{\mathrm{coll}}}$$

where n_e is concentration of free electrons, e is charge of the electron, m_e is mass of the electron, and ν_{coll} is the frequency that electrons collide with air molecules. Here, we are concerned with σ that asymptotes to the natural conductivity σ_0 far from the collector, so we use the following form instead (although the additional term may be inconsequential),

$$\sigma = \sigma_1 \, \rho(r) + \sigma_0 = \frac{n_e e^2}{m_e \nu_{\mathrm{coll}}} + \sigma_0$$

We note that $\rho(r) = n_e e$, so $\sigma_1 = e/m_e \nu_{\mathrm{coll}}$. σ_0 is known empirically from atmospheric physics and varies with storm conditions and altitude as mentioned earlier.

The mean free path between collisions of electrons with air molecules is

$$\lambda_{\mathrm{free}} = 5.6 \frac{k_B T}{\sqrt{2} \pi {d_a}^2 P}$$

where $d_a \approx 0.15 \text{ nm}$ is collisional cross section diameter of air molecules and 5.6 accounts for small size and large velocity of electrons. Average speed of electrons from purely thermal motions is

$$c_{\mathrm{avg}} = (8 k_B T_e / \pi m_e)^{1/2}$$

where m_e is the mass of an electron, k_B is Boltzmann's constant, and T_e is the electron temperature. $T_e \gg T$ when electric acceleration adds significant energy to the electrons because the much lower mass of electrons prevents effective energy transfer to the neutral molecules via collision. It may be orders of magnitude higher than *T*. We cannot estimate T_e without complex heat calculations in the region around the conductor, so we assume $T_e = 10^{\kappa} \, T$ with $0 < \kappa < 2$, which if correct means $\kappa = 1$ gives a value of c_{avg} within a factor of 3 of the correct value, which is not bad. The collision frequency for electrons is,

$$\nu_{\mathrm{coll}} = \frac{c_{\mathrm{avg}}}{\lambda_{\mathrm{free}}} = \frac{\sqrt{\pi (T_e/T)} {d_a}^2 P}{1.4 \sqrt{m_e k_B T}}$$

The time between collisions is $t_{\mathrm{coll}} = {\nu_{\mathrm{coll}}}^{-1} = 7 \times 10^{-12}$s. During this time, the electric field accelerates the electron to an additional radial velocity of $v_{\mathrm{E}} = t_{\mathrm{coll}} e E / m_e = (V_0/r)(t_{\mathrm{coll}} e / m_e)$. This defines minimum distance r_{therm} outside of which the velocities are relatively thermalized, $v_{\mathrm{E}} < c_{\mathrm{avg}}$. For *P* ≈ 100,850 Pa (typical clear sky value at $h_0 = 39.6$ m), this yields the constraint $r_{\mathrm{therm}} = 0.14$ m. This is sufficiently small that we can use the approximation to study the region far outside this radius, where $\sigma_1$is decoupled from the electric field and charge density, resulting in much simpler equations.

We must remember this thermal assumption is not accurate in the region $r{\sim}0.14\text{ m}$. In this thermal approximation,

$$\sigma_1 = \frac{e}{m_e \nu_{\text{coll}}} = 1.4 \frac{e}{{d_a}^2 P}\sqrt{\frac{k_B T_e}{\pi m_e}}$$

Using our assumption for $T_e \approx 10T$ yields $\sigma_1 \approx 11.1$ This gives us the second equation to relate E and ρ:

$$\frac{I_0}{4\pi r^2} = (\sigma_1\,\rho(r) + \sigma_0)E(r)$$

where I_0 is determined by the rate-limiting physics in the boundary layer of the collector. We non-dimensionalize this equation with

$$\hat{I} = \frac{I_0}{4\pi R_0\, V_0 \sigma_0}$$

$$\hat{a} = \frac{\sigma_0 {R_0}^2}{\sigma_1\, \epsilon_0 V_0}$$

$$\hat{I}\hat{a} = (\,p(x) + \hat{a})x^2\mathcal{E}(x)$$

This system of equations describes behavior of a spherical ion collector power system:

$$\begin{matrix} \frac{\partial}{\partial x}\left(x^2\mathcal{E}(x)\right) = x^2 p(x) \\ \hat{I}\hat{a} = (p(x) + \hat{a})x^2\mathcal{E}(x) \end{matrix}, \qquad x > 0$$

By definition, $\mathcal{E}(1) = 1$. Evaluating the second equation at $x = 1$ ($r = R_0$) gives

$$p(1) = \hat{a}\big(\hat{I} - 1\big)$$

Evaluating the first equation at $x = 1$ gives

$$\mathcal{E}'(1) = \hat{a}\big(\hat{I} - 1\big) - 2$$

So the slope is positive when

$$\hat{I} > 1 + \frac{2}{\hat{a}}$$

$$\frac{I_0}{4\pi R_0\, V_0\sigma_0} > 1 + \frac{2}{\frac{\sigma_0 {R_0}^2}{\sigma_1\, \epsilon_0 V_0}}$$

$$\frac{I_0}{4\pi {R_0}^2} > \frac{V_0\sigma_0}{R_0} + \sigma_1 \frac{2\epsilon_0(\,V_0)^2}{R_0 {R_0}^2}$$

$$J(R_0) > \left(\sigma_1 \frac{8\pi\epsilon_0 V_0}{{R_0}^2} + \sigma_0\right) E_{R_0}$$

$$\text{But,} \qquad J(R_0) = (\sigma_1 \rho(R_0) + \sigma_0) E_{R_0}$$

$$\text{So,} \qquad \rho(R_0) > \frac{8\pi\epsilon_0 V_0}{{R_0}^2}$$

If this were the case, the maximum free electron density $\rho_{\max}$ would be at some $r > R_0$. However, with the numerical values we are using this is not the case, so the maximum free electron density is very close to the surface of the collector and monotonically decreasing.

Combining the two equations,

$$x^2 \mathcal{E} + \frac{2}{\hat{a}} x \mathcal{E}^2 + \frac{1}{\hat{a}} x^2 \mathcal{E}\mathcal{E}' = \hat{I}$$

and solving it numerically in Mathematica, we get the behavior shown in the following figure for the numerical values we are using.

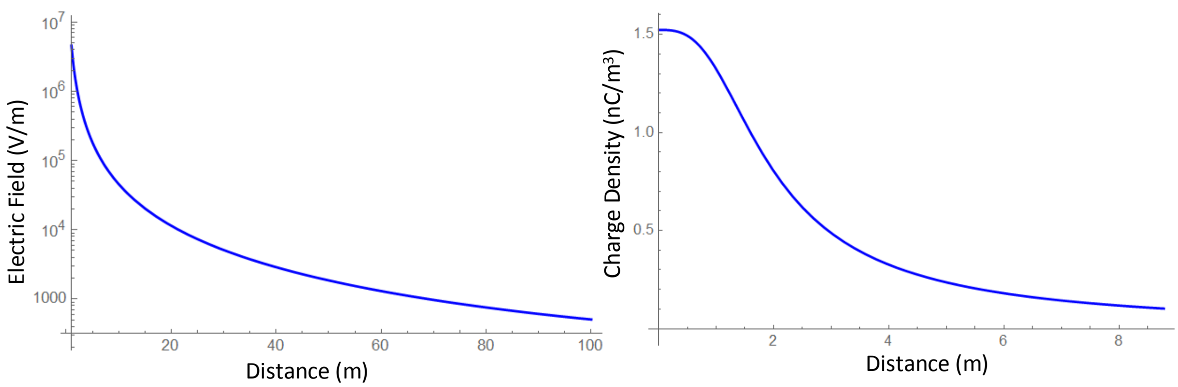
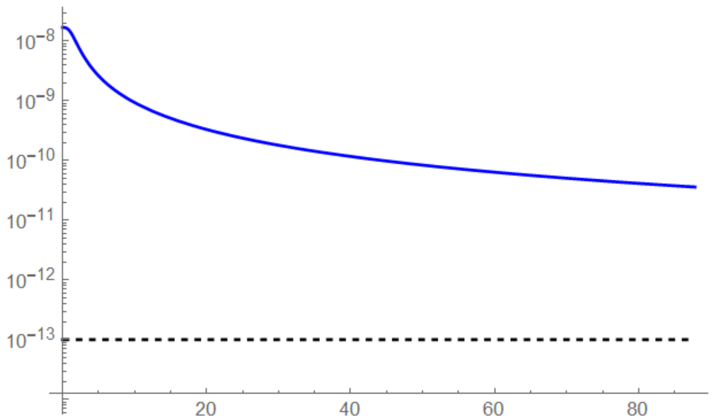


Figure: Behavior of the system of equations for the tested ion collector values. Left: Semilog plot of electric field intensity. Right: free electron charge density.

The conductivity of the air around the ion collector is shown in the following figure. Even 80 meters from the collector, the conductivity is significantly above the background conductivity $\sigma_0 = 10^{-13}\,\mathrm{mho/m}$ shown as the black dashed line. This enhanced conductivity allows electrons to flow away from the collector completing the power generation circuit, and it is caused by the presence of the free electrons themselves.



Blue: conductivity of the air (mho/m) as a function of distance from the collector (m). Dashed: natural conductivity of air without collectors affecting it.

The solution is a family of curves for different values of Ihat and ahat, as shown in the figure.

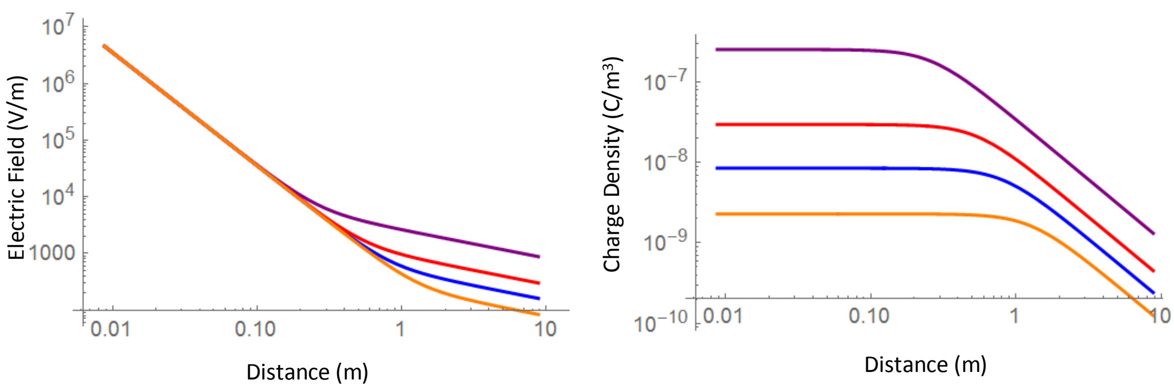


Figure: Behavior of the system of equations illustrated by the following sets of values, where $\hat{a}_0$ and $\hat{I}_0$ are the nominal case. Blue: $\hat{a} = \hat{a}_0$ and $\hat{I} = \hat{I}_0$. Purple: $\hat{a} = 100\ \hat{a}_0$ and $\hat{I} = 0.3\ \hat{I}_0$. Red: $\hat{a} = 0.5\ \hat{a}_0$ and $\hat{I} = 7\hat{I}_0$. Green: $\hat{a} = 3\ \hat{a}_0$ and $\hat{I} = 0.09\ \hat{I}_0$. Left: Log-Log plot of electric field intensity. Right: Log-Log plot of free electron charge density.

It is found empirically that the curves can be made to collapse (at least to excellent approximation in a range of parameters near the nominal case) with the following scaling:

$$y = \frac{x}{(\hat{a}\hat{I})^{1/3}} = \frac{r}{(\hat{a}\hat{I})^{1/3} R_0}$$

$$\mathbb{E} = \frac{\mathcal{E}}{(\hat{a}\hat{I})^{2/3}} = \frac{R_0 E}{(\hat{a}\hat{I})^{2/3} V_0}$$

$$\mathbb{p} = \frac{p}{\hat{a}\hat{I}} = \frac{{R_0}^2 \rho}{\hat{a}\hat{I}\epsilon_0 V_0}$$

This is shown in the following plots, where dashed lines have been adopted so that all four colors can be seen on the same curve:

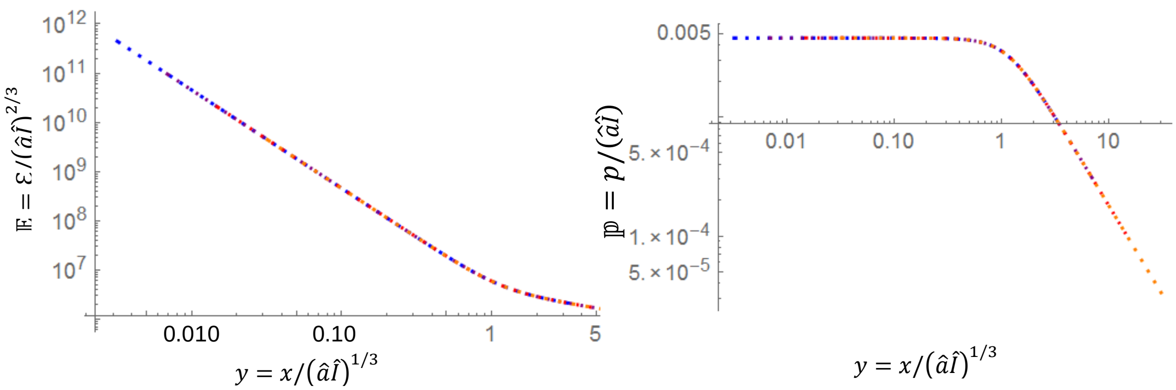


Figure: Same four cases as the previous figure but with rescaling described in the text. Left: Log-Log plot of rescaled electric field intensity. Right: Log-Log plot of rescaled free electron charge density.

We can see from the figure that there is an electron cloud around the collector with characteristic radius $y = 1$, or

$$r_{\text{cloud}} = \left(\frac{I_0 {R_0}^4}{4\pi\epsilon_0\sigma_1 {V_0}^2}\right)^{1/3}$$

Voltage is in the denominator because stronger electric field pulls the electrons away from the collector more rapidly. However, the current I_0 also scales with voltage (not shown here), so the complete scaling with voltage is not shown.

To summarize behavior of this system, free electric charge builds up in the space around the collectors, which modulates the electric field and current density. The electric field, current density, and charge density all decay with distance from the collector. These results provide a physically consistent understanding of how the system functions, providing confidence that the scaling is proportional to surface area and voltage as discussed above.

Economic Model

Because ion power generation is more effective in disturbed weather, whereas solar power is more effective with clear skies, they are complementary in time. This will reduce the need for energy storage in the smart grid and allow renewables to gain a higher market share to displace carbon-based energy sources. To illustrate this, we have written a toy model of the economics. The model assumes solar PV with energy storage is utilized for baseload power. Ion power is added to replace PV for some fraction of the total demand. PV costs including installation and maintenance are assumed at $5.70/Watt with 20 year replacement, while power storage is $200/kWh capacity with 10 year replacement. A model for random storms is added to the usual solar diurnal variations. The storm model results in a capacity factor of 25.2% for the PV system, which is comparable to the best possible capacity factors in the world. For comparison, the Agua Caliente Solar Project in Arizona has a capacity factor of 29.1%,[3] while the Lauingen Energy Park in Bavaria, Germany has a capacity factor of 12.0%.[4] Therefore, the storm model is not unreasonable. Furthermore, since this analysis uses the best possible case of capacity factor for PV, Ion Power will be even more economically successful in other parts of the world where PV capacity factor is less. This is therefore a conservative, worst-case study for Ion Power. (Additional work is needed to confirm reasonableness of the storm model and the ion power generation model, however.)

The demand model is cyclic with peak demand near 4 p.m. and minimum near 4 a.m. based on power industry data.[5] Power storage is scaled so that demand is met throughout the simulated period despite clouds and nighttime. Generation capacity is scaled to adequately meet demand while replenishing storage. This toy model results in a cost of 9.8¢/kWh for PV, which successfully replicates the actual levelized cost of electricity (LCOE) via PV predicted in the US in 2024[6], successfully validating the model. The Energy Information Administration predicted in 2015 that the grid-average LCOE for PV will be 12.5¢/kWh in 2020.[7] We estimate below that the cost of Ion Power generation is $0.088 per Watt with 20 year replacement, so PV is 65 times more expensive per Watt but with a much higher capacity factor since ion power generates full capacity only in storms.

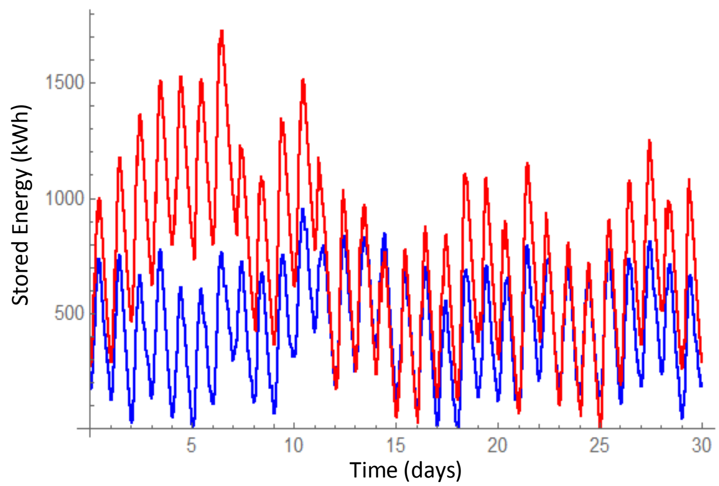


Figure 1. Stored energy over a one-month period. Red: PV alone providing baseload power. Blue: Mixture of 72.5% PV and 27.5% Ion Power generation. Note that Ion Power significantly reduces the necessary power storage on the smart grid, dramatically lowering the cost of renewable energy.

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[3] "Agua Caliente Solar Project, Monthly," Energy Information Administration, *https://www.eia.gov/electricity/data/browser/#/plant/57373/?pin=ELEC.PLANT.GEN.57373-SUN-ALL.M&linechart=ELEC.PLANT.GEN.57373-SUN-ALL.M*

[4] Gehrlicher Solar AG weiht größtes Solar-Kraftwerk Schwabens, http://www.greentech-germany.com/gehrlicher-solar-ag-weiht-groesstes-solar-kraftwerk-schwabens-25-7-mwp-offiziell-ein-a16511.

[5] Tony Ramunno (Dir. Eng. & Proj. Mgmt), "Maximize Minnesota Power Supply And Demand," Great River Energy (2nd largest utility in Minnesota), February 2010, https://www.slideshare.net/mnceme/power-supply-and-demand.

[6] Ivin Rhyne, Joel Klein, and Bryan Neff (2015), "Estimated Cost of New Renewable and Fossil Generation in California," Report No. CEC-200-2014-003-SF, California Energy Commission, http://www.energy.ca.gov/2014publications/CEC-200-2014-003/CEC-200-2014-003-SF.pdf.

[7] http://www.eia.gov/forecasts/aeo/electricity_generation.cfm

We ran the model in this configuration for 201 cases with different percentages of total power supplied by Ion Power and the rest supplied by PV, re-scaling the storage needs for each case. The total stored energy in a monthly period for one of these cases is shown in Figure 1. The 24-hour periodic component has reduced amplitude in the blue plot where ion power is feeding into the grid, because significant amounts of power are generated at night across the grid wherever there are storms. Even more significantly, the blue plot is "better behaved" and does not wander as far day-by-day because the unpredictability of cloudy days is mitigated. This greatly reduces power storage needs across the smart grid, making renewable energy more affordable and enabling it greater market penetration to displace carbon-based fuels.

Figure 2 shows the reduction in storage on the grid as a result of the time-complementarity of Ion Power, as a function of what fraction of the grid's total power is provided by Ion Power. This plot does not change depending on the generation costs of either Ion Power or PV. It is purely a function of the timing of generation for each source and the relative size of each source.

Figure 3 shows the resulting net energy cost for different mix ratios of PV and Ion Power. This is a function of the generation costs of PV and of Ion Power and of the cost of storage. In this case, PV and Ion Power were assumed to have the same generation cost per Watt, which greatly over-estimates the true cost of Ion Power and therefore is an extremely conservative, worst-case model. It proves that even in worst-case, Ion Power has benefits because of the time-complementarity of its power generation. The optimum mix ratio occurred in this model when Ion Power provided 24.8% of total energy to the grid, lowering net electricity cost from 9.8¢/kWh to 8.29¢/kWh, a reduction of 15.5% for an annual direct benefit of $62 Billion to the US economy in addition to the indirect environmental benefits. Global

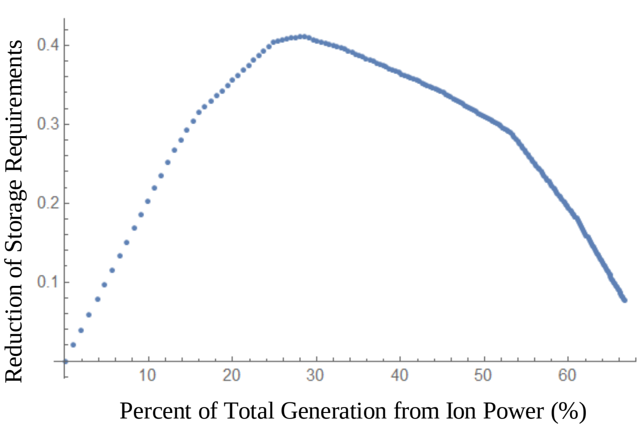

Figure 2. Percent that baseload energy storage requirements are reduced by adding Ion Power to a grid that is otherwise based on PV. Horizontal axis is the percentage of energy generation provided by Ion Power (the remainder being solar PV). Minimum grid storage is when Ion Power provides close to 30% of total power generation.

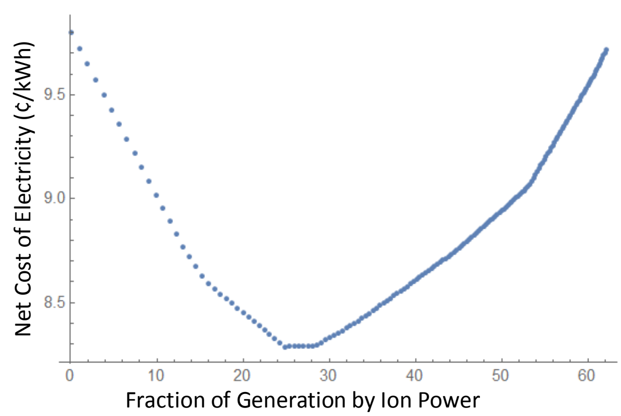

Figure 3. Net cost of electricity for different mixtures of PV and Ion Power in the toy model. This is for over-estimated Ion Power costs. Each dot represents one simulation. Lowest net cost occurs when Ion Power provides 24.8% of total energy to the grid. The slope discontinuities occurred naturally and are not an artifact.

benefits will be proportionately higher. Because we assumed Ion Power generation is as expensive as PV, this reduced cost is entirely due to reduced need for storage. More realistically, Ion Power will be far less expensive than PV.

Method to scale up power collection to economic levels

In the following economic analysis, we assume collectors are spherical aerostats and that power collection can be scaled up via these methods:

1. Put the collectors at higher altitude so they exist inside a region of the atmosphere that has higher voltage. Per generally accepted atmospheric physics the ionic voltage at 10,000 feet altitude is 500,000 volts (12x higher than in the prototype tests).
2. Increase the surface area of the collectors. The surface area of a single collector had a surface area the same as a sphere that is 8.78 mm radius. A 30 m aerostat would have a radius 3,417 times as large.
3. Dividing voltages more optimally between ground and sky. The prototype test measured 41,200 v in the air and used a 1000 v drop across power generation circuits, which meant 40,200 v was spent across the electron cloud surrounding the collector. If the 500,000 v potential is divided so 250,000 v is across the power generation circuits then the voltage on the collectors is still 6.2 times higher, but power captured at the ground is maximized per the maximum power transfer theorem.

During ground test at the Florida test site, the current generated by each collector in peak conditions was 75 µA at 1000 v (on the ground circuitry) for 75 mW power. Scaling up the current by a factor of 6.2×3,417 yields 1.59 Amps. At 250,000 volts this produces 397 kW power at the ground, an increase of 5.3 million times.

Table 1. Cost Estimate provided by Ion Power Group.

Item	**Cost Estimate (production scale)**
7 each Aerostats (to replace 6 times in 20 years)	\$1000 x 7 = \$7000
Tether (20 year replacement)	\$7000
Winch (20 year replacement)	\$1000
Annual Maintenance	\$1000 x 20 = \$20000
Total 20-year cost for 397 kW	\$35,000
Cost per Watt	*\$0.088*

Table 2. Cost estimate based on other commercial aerostats

Item	Cost Estimate (production scale)
Aerostat	$200,000
7 each surface treatments (to replace 6 times in 20 years)	$10,000 x 7 = $70,000
Annual Maintenance	$10,000 x 20 = $200,000
Total 20-year cost for 397 kW	$470,000
Cost per Watt	*$1.18*

Table 1 is a cost estimate provided by the Ion Power Group. This estimate suggests the power generation cost will be $0.088/Watt. We re-ran the toy model assuming (conservatively) twice this amount, or $0.175/Watt for Ion Power (20 year replacement). Figure 4 shows the net cost of electricity for different mixes of Ion Power and PV with this estimate.

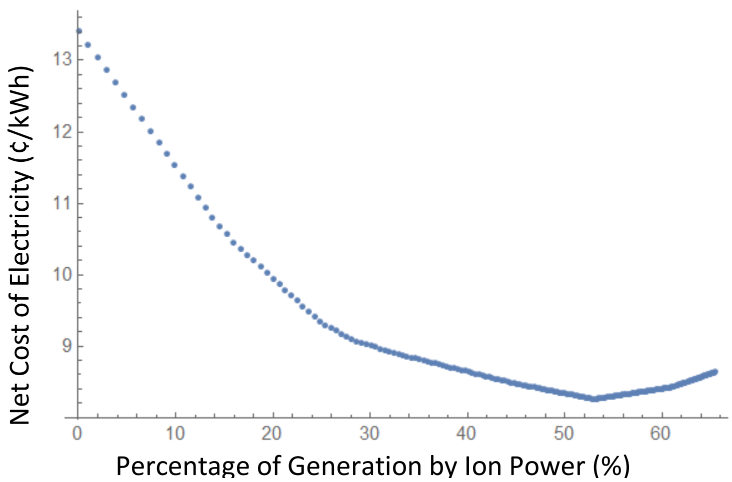

Figure 3. Net cost of electricity for different mixtures of PV and Ion Power in the toy model using more realistic cost estimates.

This shows the optimum mix is 53% Ion Power and 47% PV for net electricity cost of 8.26¢/kWh, a reduction in cost of $5.14, or 38%, for a direct annual benefit to the US economy of $150 Billion, plus indirect environmental benefits. Global benefits will be proportionately higher.

Table 3 shows a cost estimate based on other existing, commercially-available aerostats that operate at very high altitude. This may be different than the operating conditions of Ion Power aerostats, but is provided here to create greater confidence in the conclusions of this study, since these are actual costs of operational aerostats. This suggests the power generation cost could be $1.18 per Watt. Note that in the section above, an analysis showed that even if Ion Power had a cost as high per Watt as PV (about $5.70 per Watt), then including it on the grid will produce $62 Billion benefit to the US economy. Therefore, a $1.18 per Watt cost would produce somewhere between $62 Billion and $150 Billion annual benefit to the US economy. This wide range provides very strong confidence that Ion Power is economically viable since it very likely encompasses the actual costs that will be determined by a more detailed analysis.

Table 3 shows the predicted levelized cost of electricity in 2024 for the most common energy sources, as estimated by the California Energy Commission.[8] (Note that this is cost per kWh, not production cost per Watt.)

Energy Source	Cost per kWh
Wind Class 3 100MW	7.5¢
Wind Class 4 100MW	7.5¢
Solar Photovoltaic (Thin Film) 100MW	8.1¢
Solar Photovoltaic (Thin Film) 20MW	9.3¢
Solar Photovoltaic (Single-Axis) 100MW	9.8¢
Solar Power Tower With Storage 100MW 11HR	10.4¢
Solar Photovoltaic (Single-Axis) 20MW	10.9¢
Geothermal Binary 30MW	11.0¢
Solar Parabolic Trough With Storage 250MW	11.7¢
Solar Power Tower With Storage 100MW 6HR	13.3¢
Solar Power Tower W/O Storage 100MW	13.4¢
Geothermal Flash 30MW	14.4¢
Biomass Fluidized Bed Boiler 50MW	15.4¢
Solar Parabolic Trough W/O Storage 250MW	15.6¢
Combined Cycle 2CTs With Duct Firing 500MW	16.7¢
Combined Cycle 2CTs No Duct Firing 500MW	16.7¢
Generation Turbine – Advanced 200MW	53.3¢
Generation Turbine 100MW	88.2¢
Generation Turbine 49.9MW	88.4¢

We see that Ion Power has the potential to produce electricity at the very lowest end of the cost scale. Only Wind Class 3 100MW and Wind Class 4 100MW can produce marginally less expensive power, but these generation methods are extremely limited in geographical application.

Conclusion

I conclude that Ion Power is likely an economically viable technology, competitive in a grid mix with other energy sources. It is likely that it will not only out-compete many other renewable energy sources, but it will also lower the overall cost of electricity on the grid because of the time-complementarity of its power generation. Ion Power is an excellent candidate for further development, beginning with simple laboratory tests to validate the scaling relationships, thus achieving TRL-4, followed by full-scale breadboard prototype testing with an aerostat to achieve TRL-5, then high fidelity prototype testing to achieve TRL-6. Because of the need to rapidly transition to renewable energy sources, this development should begin immediately.

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[8] Ivin Rhyne, Joel Klein, and Bryan Neff (2015), "Estimated Cost of New Renewable and Fossil Generation in California," Report No. CEC-200-2014-003-SF, California Energy Commission, http://www.energy.ca.gov/2014publications/CEC-200-2014-003/CEC-200-2014-003-SF.pdf