IMPERIAL COLLEGE

Lightning Harvest

- as an energy resource for rural communities

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Table of Contents

Introduction

Many people in the Democratic Republic of the Congo (DRC) are without a consistent energy source, and are subjected to frequent and consistent thunderstorms throughout the year. It is also financially unviable to connect rural areas to the country's main energy infrastructure. In considering these factors, the provision of small lightning capture facilities to harness this yet untapped natural, renewable energy source has been proposed. It is believed that the quality of life for the impoverished in these areas can be improved by providing them with low cost energy by harvesting lightning.

Nature of Lightning

Lightning is a surprisingly complex phenomenon, and it has a number of properties that present challenges for those wishing to harness it. Discussing the nature of lightning comprehensively is impossible, but there are some basic features of lightning that bear description.

Lightning occurs when charge builds up in a layer of cloud in the atmosphere, inducing an electric field between the earth and the clouds, which causes molecules in the air to become ionised, allowing the air to become a temporary conductor to discharge the natural capacitor (Figure 1).

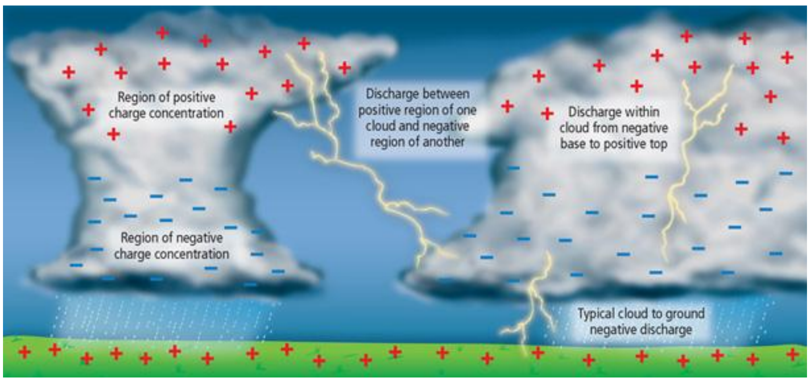

Figure 1 Charge distribution in clouds and the ground[1]

This build-up of charge occurs as a result of precipitation and the convection currents selectively separating charges in a thundercloud. The Elster-Geitel model describes water droplets in the cloud travelling upwards as a result of convection (itself caused in part by the heat exerted by vaporisation) collecting positive charge from ice particles which have been polarised by an electric field. The polarisation of the ice particle means the bottom is more positive than the top, so a neutral water droplet travelling upwards would collect some of its positive charge. This would cause a separation between positive and negative charges in the cloud. This process has positive feedback as the resulting voltage contributes to the electric field. Of course, an electric field must exist beforehand, but only a small field is needed to trigger the process. [2]

Air is ionised at an electric field strength of 3MV m^{-1}. At this strength, electrons in the atoms gain sufficient energy to elevate in energy levels. The outermost electrons are ejected from the atom, providing free charges (electrons and ions) in the air. These free charges are affected more by the electric field when free from the pull of the nucleus. The potential difference between the clouds and the earth at time of ionisation has been given as around 100 - 120MV.[3][4]

A lightning occurrence that successfully hits the earth has a stepped leader, which is the first stroke that propagates. This stepped leader, which travels in a stream about 45 metres long, is caused by ionisation in the clouds when discharge occurs in the cloud layer, where there are differences in potential. The electrons freed from this process are attracted to the ground. As the leader travels towards the earth it generates a channel of ionised air. Just as the negatively charged stepped leader reaches the earth, it attracts positive charge from the surface of the earth towards it, inducing a large current, causing the air surrounding the leader to become luminous. The positive charge then travels up this channel, illuminating the air as it goes. This is what is known as the return stroke and is what is visible to the observer. Even though the return stroke only illuminates the air while it is travelling, it is perceived as a solid line because it happens too quickly for human vision to see the movement.[5]

Nature of Demand

For the output stage, many possibilities were explored. It was put forward that there would be transmission lines from the facility to some sort of long-distance grid, or perhaps directly to the communities that would benefit. The problem with transmission of power is that if there were to be step down transformers along the way to control the voltage supplied to the settlements, the output would need to be AC. There would be issues in the production of large scale AC, lowering efficiency. DC transmission was also considered, but the power losses in the lines could only be solved by providing a large voltage and a small current, which would later be difficult to transform. Any form of transmission will also be wasteful for the type of small community that this project considers, as there may be long periods during which no-one is using the power.

Upon research of power usage in rural Africa, it was found that in Kenya, small communities rely heavily on batteries. Dry cell batteries can be used for small loads, but car batteries are necessary for larger ones.[6] It was then suggested that a system is developed to charge car batteries that can be supplied to communities in the DRC, allowing for relatively efficient, portable, and versatile power supply.

A standard lead-acid car battery outputs around 12V, but is charged using a 14V supply.[7] There is usually a maximum charging voltage, above which the water in the battery begins to electrolyse and produce oxygen and hydrogen. Hydrogen in an oxygen rich environment is dangerous, as a spark can ignite it, causing an explosion. To avoid this, the voltage across the terminals of the battery should be kept below 14.4V.[8]

One problem with charging the batteries is the time it takes to reach operational voltage. A single cell in a battery (of which there are usually six in series) reaches 70% capacity in around 5-8 hours, and the rest over 7-10 hours,[9] at a constant current. This means that the system that charges the car battery must dissipate the energy received from the lightning strike over the course of 18 hours, at a DC voltage of 14 to 14.4 V.

Overall System Flowchart

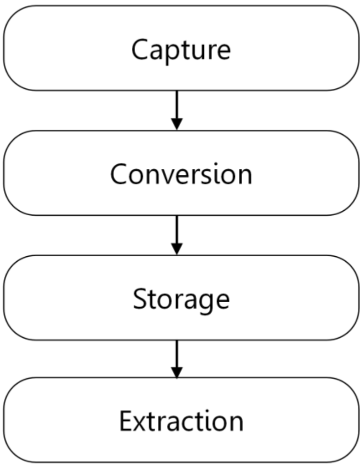

Figure 2 shows a simplified model of the steps necessary to convert the energy from a lightning strike into a form suitable for charging car batteries.

For this project, the conversion, storage and extraction stages were given the primary focus. It has been assumed that a system would be in place that would allow the lightning to be captured efficiently.

Various options for the remaining stages are detailed below.

Figure 2 – High level flowchart of the system

Capacitive Circuitry

The lightning strike is assumed to be captured as a high power impulse whilst the output should be low voltage DC. Another consideration is the duration of the input; a small yet constant output is desired. These characteristics form the basis of any requirements of an electrical conversion system.

The duration of any lightning strike is of the order of microseconds[10] whilst the desired output is required to charge car batteries, needing a time scale of hours.[9] This serves as the primary motivation to consider a capacitor bank to store the energy initially as the power to the batteries cannot all be safely transferred instantaneously. The capacitors could then be discharged through an electronic switch, such as an insulated-gate bipolar transistor (IGBT) and converted to a lower voltage suitable for a battery. Therein lies the central problem in using certain conversion designs (e.g. Step-down transformer) as usually there is either a voltage or current magnification, whilst the output waveform is largely unaltered.

To solve this problem a large capacitor bank could be charged by the impulse, after which the discharge could be controlled. The storage capacitor could then be coupled to a conventional buck converter, allowing control over the discharge of the capacitor through switching.

As the desire is to store as much energy as possible from the impulse, supercapacitors appear to be a natural choice. However, their low rated voltage, typically in the range of a few volts, makes then ill-suited to the input stage. Higher voltages cause hydrogen gas to form which is incredibly dangerous.[11]

Since supercapacitors are unfeasible under this constraint, capacitor technologies must be considered. For high power conversion aluminium electrolytic capacitors are often used as they have large capacitance per unit volume. Drawbacks include a larger leakage current and effective series resistance (ESR) compared to other technologies. [12] A more suitable candidate for the initial storage of the impulse is power film capacitors, often used in high voltage applications such as lasers and particle accelerators, as they are capable of handling large pulse currents for short periods of time.[13] This makes them ideal for absorbing a lightning strike.

One dielectric material used in power film capacitors is polypropylene. Despite the relatively low relative permittivity of polypropylene compared to aluminium, they offer many advantages over the latter, such as very low ESR, excellent stability (especially compared with wet aluminium capacitors which dry out), and low effective series inductance. However, its capacitance per unit volume is quite low. [13]

Another dielectric used for electrolytic capacitances, tantalum pentoxide, has the lowest leakage current for any electrolytic capacitor, a high relative permittivity and is very reliable, but it will be irreparably damaged if the ripple current is exceeded.[14]

Once the energy is stored in the capacitor bank, it must be connected to a conversion system which will reduce the voltage to 14V. The most efficient approach to do this is to employ a switch-mode power supply (SMPS). The basic operation uses switching action of a MOSFET (or other electronic switch) to regulate the charging of an inductor and other passive elements to produce a desirable average output voltage. The theoretical maximum performance of a SMPS can be 100% but a very well designed buck converter may have 95% efficiency as there are always parasitic impedances. There are numerous converter topologies, some of which include transformers, while others contain multiple MOSFETs to gain efficiency at the cost of circuit simplicity.

Assuming the best case, the overall efficiency from capacitor to SMPS would be 47.5% (50%×95%) but perhaps a more reasonable estimate would be 30% or lower. The precise value would depend on the specific design and the nature of the lightning strike itself.

In principle the energy could be stored and converted in the manner described, but the very high power involved prevents would mean using expensive capacitor banks to handle the unpredictable voltages and huge current surges, with current rise rates in excess of $10^{11}\mathrm{As}^{-1}$. The voltage at the lightning conductor could be a hundreds of kV, but it may a magnitude or two greater. [10]

These issues make stepping down using an SMPS difficult as the difference in input and output voltages is very great, leading to very low periods of ‘on’ time of the SMPS. In particular, this approach suffers from the unpredictability of the lighting impulse, the expense of the system for what is a small-scale solution and the high risk to electrical equipment, as any sensitive equipment will also need to be shielded and the capacitors are liable to cause electrical fires or explosions.

Hydrogen Storage

An alternative method of converting the energy in a lightning strike is to store it in hydrogen, produced through the splitting of water. This can be done by several mechanisms, such as electrolysis and thermal splitting.

Electrolysis is the phenomenon in which molecules become ions when a large voltage is applied across electrodes. When this procedure is applied to water molecules, it produces hydrogen and oxygen ions, which form into their respective element molecules.[15]

Electrolysis could be achieved via the following process: the high voltage of a lightning drives a pair of electrodes, which are stuck into a tank of water. The lightning will provide a large direct current, which will break down the water molecules into hydrogen and oxygen. The two gaseous products can then be easily separated from the liquid water in the tank. In addition, the hydrogen will be attracted to the cathode, whereas the oxygen will be attracted to the anode, and hence it is simple to separate the two gases.

In addition to electrolysis, hydrogen can also be produced by thermal splitting, in which water molecules break down into hydrogen and oxygen when heated. The temperature required for this process is $\sim$2000K, although more splitting occurs at higher temperatures.[16]

Regardless of the method used to produce it, the hydrogen can then be stored in a fuel cell, and can then be used to produce energy at a later time.

Unfortunately, hydrogen storage can be problematic. Fuel cells are themselves inefficient (efficiency tends to be somewhere between 40 and 60%), creating another stage of the process in which energy is lost.[17]

The oxygen produced by both processes (electrolysis and thermal splitting) is largely a waste product, lowering the efficiency of the system further.

Health and safety, however, is by far the most important disadvantage to the use of hydrogen storage. Hydrogen is both flammable and explosive, so great care must be taken when dealing with it. In particular, a system that produced hydrogen using lightning would likely have no way of protecting itself against multiple lightning strikes occurring in quick succession, and the consequences could be catastrophic.[18]

Introduction to Thermal Storage

With both capacitive conversion and hydrogen storage ruled out, the best remaining option is to store the energy thermally. The energy is stored as heat in a medium with either a high specific heat capacity or latent heat, and can then be extracted at a later time, for example by driving a turbine, or through thermionic generation.

Thermal storage avoids some of the problems of the other conversion mechanisms, specifically with regards to protection against relatively powerful lighting strikes. Since no electronics are used until after the energy has been stored, there is less chance of damage, and by using a sufficiently large medium with a high volumetric energy density, overloading of the system can be avoided.

Heating Elements

Most heating elements are made of copper due to its high thermal conductivity. Since the lightning conductor would likely also consist of copper, this means the system would only require a single material if copper were to be used.

The maximum power transfer theorem states that the maximum power transfer to a load (the heating element) occurs when the load resistance is equal to that of the source. In this case, the source consists of the lightning conductor and the lightning channel. Due to the unpredictable nature of lightning, the resistance of the channel is not constant, so it is not possible to design the element to be a matched impedance. However, a high impedance can be targeted to give a greater efficiency. This is the case as $\frac{R_{load}}{R_{load}+R_{source}} = \frac{1}{1+\frac{R_{source}}{R_{load}}}$, so minimising the source resistance (resistance of the conducting tower) and having a larger load resistance is desirable. Note that the efficiency is unity when the load resistance is infinity, but then there is no power transfer. If a dissipated energy of 200 MJ and a current of 30kA which lasts for 200ms[10] is considered, then a 1.1 Ω resistance is required, given by $R = \frac{E}{I^2 t}$. This calculation has to be performed using the upper threshold of energy, but if the duration of the current is shorter or the average current is lower, the resistance needed to dissipate that energy is much greater. Therefore, it is desirable for the resistance of the heating element to be greater than 1.1Ω.

To give the highest rate of heat transfer the surface area of the conductor should be maximised. An example of a potential heating element is shown in the diagram below, in Fig 3.a.

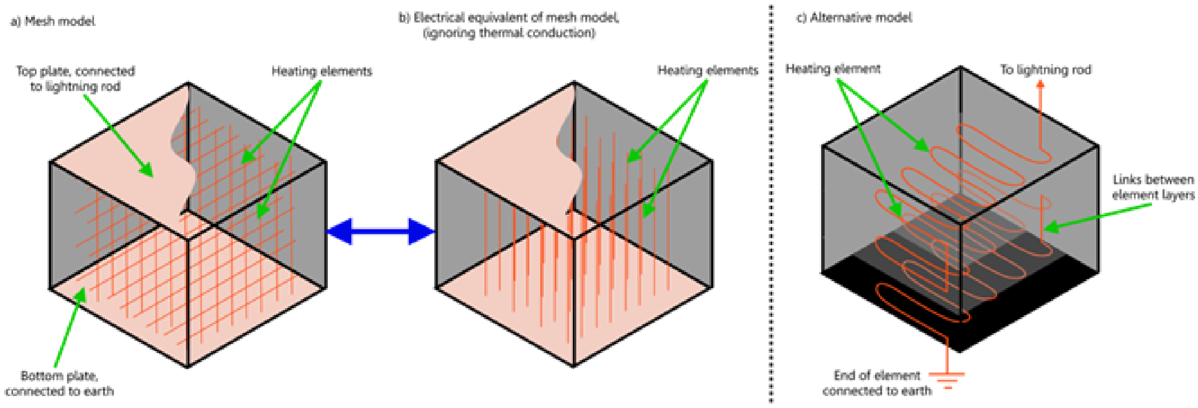

Figure 3 - Different arrangements of heating elements

To model this system the copper adjoining every node can be considered as a resistor, creating a 3D network of resistors with the top surface connected to the lightning conductor and the bottom surface connected to ground. By inspection it can be deduced that the voltage at any point on a horizontal plane is the same, so resistors that lie in the horizontal plane can be omitted. Through this simplification the heating element can be modelled as a bank of resistors in parallel for each copper conductor connecting the input to ground. This simplification is shown in Fig 3.b.

If a single wire has a radius of 1mm and a length of approximately 80cm then the resistance is 0.429Ω.[19] As this would be in parallel with many other strands the total resistance would be further reduced. As a consequence a mesh would be unsuitable for this project's purposes. Although the radius of the wire could be decreased, or a material with a lower thermal conductivity could be used, there is a far greater alternative.

If it is desired to vastly increase resistance then increasing the length or the resistivity of the conductor are the only possibilities, $R = \rho \frac{l}{A}$. To increase the length and thus the resistance a winding copper wire can be created that runs back and forth along the length of the cube. The arrangement is repeated throughout the entire depth of the concrete block (approx. 80cm). Such a configuration is shown in Fig 3.c.

If the separation between the windings of copper is 1cm both in the horizontal and vertical plane, and the radius of the wire is 1mm then the total resistance is 28 Ω. The number of windings per layer, $n = \frac{w}{d_s} = \frac{0.8\text{m}}{0.01\text{m}} = 80$. If the distance from layer to layer is 0.01m, then 80 layers can be embedded in the storage material and the total length of the conductor is $l_{total} = (0.8\text{m} + 0.01\text{m})80^2 = (64.8\text{m})80 = 5184\text{m}$. From this the resistance of the wire can be calculated as $R = 1.7 * 10^{-8} \Omega \frac{m \times 5184\text{m}}{\pi (0.001\text{m})^2} = 28.05\Omega$ [19]

A wire with a thinner radius could be used, however it would need to be sufficiently thick so as not to melt. Nichrome could also be used instead of copper, as it has a resistivity of 1.0×10^{-6} [19] (over 64 times that of copper). This would increase the resistance to 1650Ω. Another aspect to consider is the electrical insulation of the conductor as the concrete is hydrated. If a 0.1mm radius copper wire is used a length of 7392 metres would be needed to give a 4kΩ resistance.

Thermal Oils

Thermal oils are extensively used in heating process applications, as a method of transferring heat from one material to another. They are possibly the ideal fluid for the purposes of the project since they can be used in a non-pressurized system, whereas alternatives, such as steam, require higher pressure. Among other things, this means that a system using thermal oils will likely be safer than one using steam.

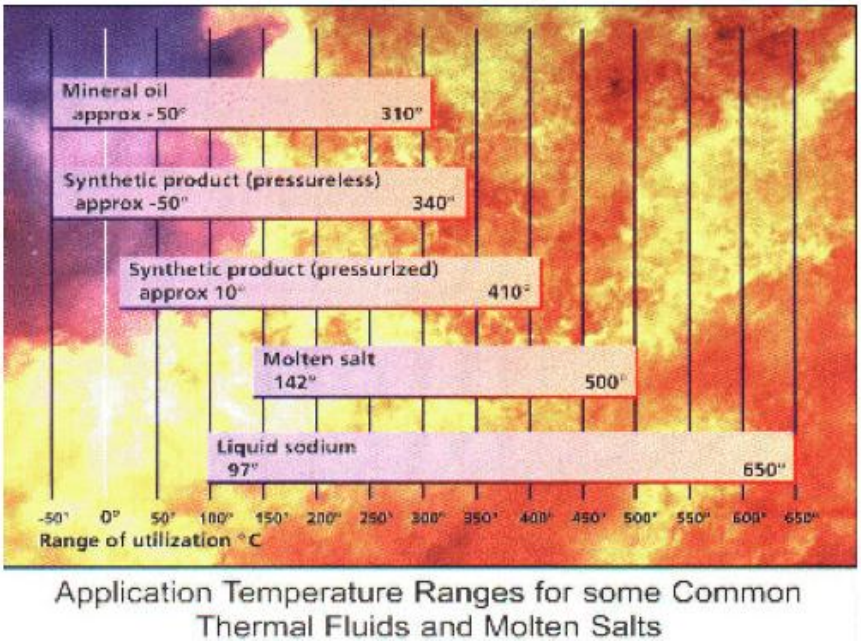

Figure 4 Heat Transfer Fluids Operating Temperature Ranges [20]

In addition, thermal oils can be up to 30% more power efficient than steam,[20] as steam may condense into water due to small changes in pressure, which would then be unusable as a transfer mechanism for the heat energy.

Figure 4 displays the operating temperature ranges of three types of thermal oils (molten salt and liquid sodium are used as comparisons).

Water

Water has a very high specific heat capacity (higher than most materials, at 4.18 J g^{-1} K^{-1}),[21] allowing more energy to be stored as sensible heat for a given mass than for a lot of other materials, including concrete. It is also far cheaper than any other storage material, so costs (at least, those associated with the storage medium) would be minimised.

However, there are several problems associated with the use of water. Firstly, since water has a density of approximately 1 g cm^{-3} [22], the amount of energy that can be stored per volume, rather than per mass, is 4.18 J cm^{-3} K^{-1}, or 4.18 MJ m^{-3} K^{-1}. Comparing this with the previously stated value for the energy density of CSA (360 MJ m^{-3}), it can be shown that an equal volume of water would need to be heated by 86°C to be able to store the same amount of energy. However, due to water's low boiling point, heating it even that much would pose a problem, as the storage medium is of no use if it simply evaporates. While a larger volume could be used, the same could be said for alternative storage media, which could then store even more energy.

In addition, if the water is impure, heating can cause precipitation. This can in turn lead to corrosion, which can cause leaks. The tank would thus need regular maintenance, although this would be difficult to do at times when it is storing energy.[23]

Finally, the rapid intense heating of water can cause it to thermally split into hydrogen and oxygen. As stated before, hydrogen is both flammable and explosive, and thus poses a safety hazard (in particular, the system would have no protection against multiple strikes occurring within a fairly short interval.

Molten salts

Another possible storage medium for the energy is molten salts (often a mixture of sodium and potassium nitrate). Much like concrete, molten salts have a lower specific heat capacity than water, but they can be heated to far higher temperatures without causing evaporation.[24]

The main disadvantage with using molten salts is that they must be permanently kept at a sufficiently high temperature for the salts to remain molten (approximately 131°C).[25] Not only would this be difficult to implement, it would also require a large amount of energy, so much so that the system would need more energy to function than it would store.

CSA

The medium that is going to be used is calcium sulfo-aluminate (CSA) concrete, a material with a very high latent heat (energy stored due to a change of state at constant temperature) of dehydration, which stores thermal energy for a long time without significant energy losses.

Compared to other heat storage materials this innovative concrete mixture has a high loss-free storage energy density >100KW h m^{-3} which is much higher than paraffin or the sensible heat (energy stored due to a change in temperature) of water[26]. The thermal conductivity of CSA concrete is high, and it is inflammable. The cost of CSA concrete is similar to that of normal concrete.

The concrete storage module is principally composed of a tube register and the storage concrete. The tube register is used for transporting and distributing the heat transfer medium (thermal oils) while sustaining the fluid pressure. The storage concrete stores the thermal energy.

Insulation

One of the challenges with storing energy thermally is in avoiding losses due to dissipation to the atmosphere. Any storage system that utilises sensible heat storage will need to be properly insulated, so that the energy can be stored for long enough to be useful.

Insulators are predominantly described by their thermal conductivities. Examples of materials with low conductivities are aerogel (a silica gel filled with pores of gas) and vacuum insulation panel (insulating sheets separated by a vacuum), which have conductivities of approximately 0.01 kW K^{-1}. However, such materials are expensive, costing up to £50 per square metre. Meanwhile, insulators with lower thermal conductivities, such as cork, wool and layered foil, cost in the region of £10 per square metre, making them much more affordable.[27]

As the conductivity of the majority of insulators increases when they are wet, their use in humid, stormy climates like that of the DRC is limited. It would therefore be a good idea to use a storage material that uses latent heat instead of sensible heat. This is another benefit to using CSA as the storage medium for the system.

Thermionic Generation

Thermionic generators turn heat into electrical energy by use of a temperature difference between two metallic plates, that are separated by a vacuum. The heat stored in the system would be used to heat the ‘hot’ plate .That would cause electrons to be emitted from its surface and be collected on the surface of the ‘cold’ plate. As a result, a charge difference will develop between the two plates, which can drive usable electric current. Thermionic generators are more efficient than steam turbines, and an efficiency of 40% can be achieved.[28] The current produced can be used to charge a car battery.

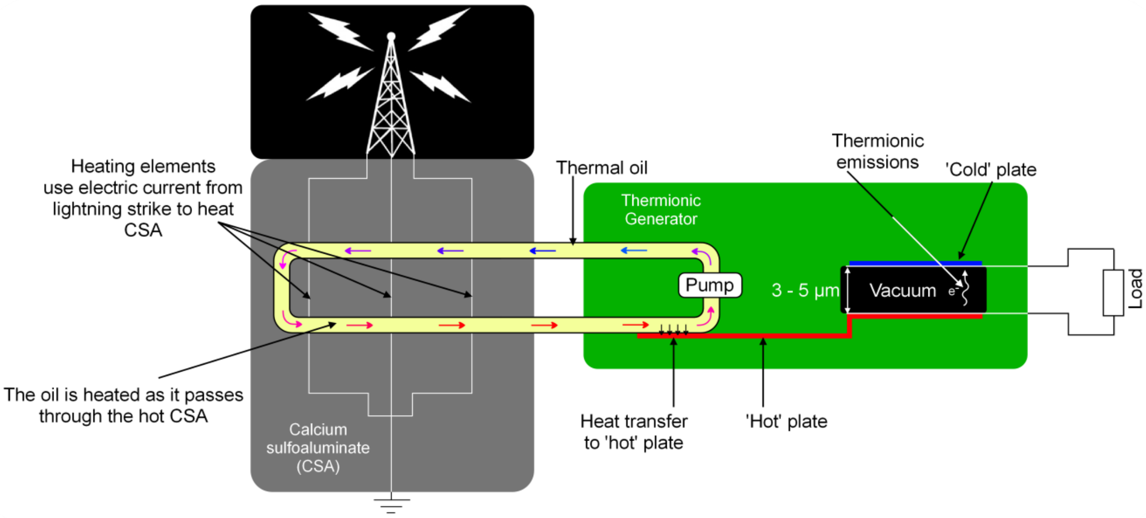

Figure 5 - Thermionic Generator

Conclusion

Based on the assumption that the power carried by lightning strikes has been successfully captured via a conducting tower, this power is transferred thermally into the heating elements. By substantially increasing the temperature of the heating elements, the thermal energy can be further distributed so that the thermal oils passing through the tubes are heated. These tubes are then passed through an innovative type of concrete (CSA) in order to transfer the energy and storing it by exploiting the properties of the CSA which above all include energy storage for later use. The tubes carrying the thermal oils extend at both sides of the concrete so that the energy contained in the oils is used to heat up the lower 'hot' plate of the thermionic generator. The temperature difference between these two plates is then used to produce a current to charge up the car batteries.

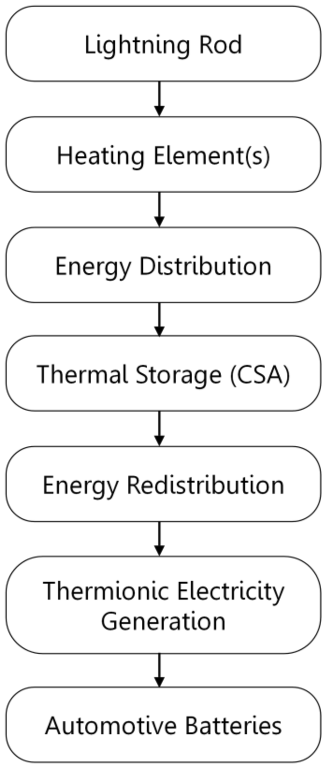

Figure 6 - Lower level system flowchart

System Parameters

Maximum energy in lightning = 10GJ [10]
Using a 50m tower:
Assuming cloud height of 3km [10]:
Energy at input to system = 50/3000 * 10GJ
= 165MJ

Volumetric storage energy density of CSA > 100kW h m^{-3} [26]
> 360MJ m^{-3}
Volume required = 165/360 = 0.46m^3
= 460000cm^3
Charging voltage of car battery = 14V
Charge in battery = 70 Ah [29] (typically)
= 252kC
Energy required to charge =252*14
= 3.5MJ

Therefore, number of car batteries that can be charged = 165/3.5

= 47

Efficiency required per battery = 2% per strike

Further Developments

Having designed the system shown above, this final section details the direction that could be taken if the project had been given more time.

The capture of lightning has not been considered in this project. Were the system to be implemented, this would obviously need to be taken into consideration, for example in the design of a lightning rod with which to capture the energy.

A control system would need to be put in place that would disconnect the storage mechanism from the lightning rod after a strike has been captured, so as to protect the system against multiple lightning strikes occurring in quick succession, and to prevent heat dissipation via the lightning capture device.

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