SPACE BASED SOLAR POWER FOR REGENERATIVE ATMOSPHERIC GEOENGINEERING AND ANTHROPOGENIC POLLUTION CONTROL

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High altitude ozone depletion and long-lived greenhouse effect contributing gases from anthropogenic sources represent a considerable threat to our ecosystem and way of life. In this paper, we propose a novel geoengineering approach exploiting space based solar power (SSP) to mitigate long-lived atmospheric pollutants via plasma discharge chemical decomposition and regeneration of depleted regions of the ozone layer from these electrical discharges. An overall conceptual description of the approach is outlined, using high energy ionizing phenomena produced either by solid-state lasers or RF induced mesosphere/stratosphere/ionosphere heating.

I. INTRODUCTION

First world and developing countries continue to produce substantial amounts of atmospheric pollutants resulting from industrial processes and over reliance on fossil fuels combined with our slow efforts to balance carbon-based fuels with those from renewable energy sources. This anthropogenic pollution is now undoubtedly contributing to the warming of our planet and will have significant implications for generations to come. In addition, the release of many halocarbons such as CCL_2F, HCFC-22 and CCl_4 (to name but a few) have already had significant impact on our atmosphere by promoting chemical reactions deleterious to the ozone layer, an important protective system that helps to shield us from damaging solar UV radiation.

It is commendable that a move towards renewable energy systems over a medium term timeframe is beginning to emerge, and a number of green technologies will likely feature prominently in translating to a more sustainable energy supply. Depending on geographical location, photovoltaic systems are already economically viable at specific latitudes and wind and tidal energy continue to develop at an encouraging pace. Along side these conventional renewable energy sources, much research has been carried out examining the feasibility and application of more esoteric avenues for energy harvesting, for example, the provision of energy from space via wireless power transmission from orbital solar arrays, colloquially known as the space solar power concept (SSP) [1].

However, even if our societies switched to carbon neutral and renewable energy in the morning, a significant amount of greenhouse gases would still persist within the atmosphere for long periods owing to their respective residence times within the various atmospheric regions. Table 1 below lists some of the more significant greenhouse gases. The greenhouse potential of some of these long residence time compounds is significant and approaches to try and "geoengineer" these gases out of the atmosphere have been suggested, most notably in the form of carbon sequestration technologies.

Greenhouse Gas	Residence Time (years)	GWP 20 Years	GWP 100 Years	GWP 500 years
$\mathbf{CO_2}$	100	1	1	1
$\mathbf{CH_4}$	12	72	25	7.6
$\mathbf{N_2O}$	114	289	298	153
$\mathbf{CCl_2F}$	13.8	3300	1300	400
$\mathbf{CH_3CF_3}$	52	5890	4470	1590
$\mathbf{SF_6}$	3200	16300	22800	32600

Table 1: Greenhouse Warming Potential (GWP) of significant greenhouse gases normalized to a comparative unit of CO_2. Values taken from the ICPT [2]

As a measure to help mitigate the influence of greenhouse gases, we propose a novel use of the SSP concept. In many ways, our concept follows the classical wireless power transmitted SSP approach, albeit with a singular modification. Specifically, space solar power systems will be used to provide continuous energy to an array of solid-state lasers (or a high power RF antennae array). These lasers can then be focused and directed at targeted regions of the atmosphere in order to induce the formation of an atmospheric air plasma discharge.

This electrical discharge will induce ionization, excitation and dissociation of the gaseous pollutants in the targeted region, producing excited molecules, ions, radicals and thermalized electrons. Any volatile organic compounds present, likely in a diluted volume, can then be efficiently catalysed by one or more of these reactive species and enter a sequence of reactions that can eventually lead to their decomposition into non-greenhouse contributing compounds or other storage molecules.

Demonstration of the decomposition and oxidation of many of these long-lived greenhouse gases has been shown previously by many varieties of plasma discharge [3]. One of the significant drawbacks to large-scale adaptation of plasma discrharges to scrub these gases from the atmosphere has been the power required, as well as their relatively slow destruction rate. SSP is uniquely suited to providing the energy for this approach. Any terrestrial based system would inherently require substantial power output in order to be effective on a large scale and the generation of that power would itself contribute to greenhouse emissions - this is a problem that a space based solution would bypass.

Two technologies are proposed which could conceivably allow for the formation of targeted plasma discharges within the atmosphere. One involves the use of state-of-the-art solid state lasing and the formation of plasma filaments. The second approach details using conventional RF antennae to ionize the atmosphere. Earth observation mission satellites would provide atmospheric information on areas of concentrated pollution or ozone depletion and ground-based measurements could further compliment the assessment. Figure 1 below illustrates the concept, whereby a SSP satellite outfitted with an array of solid-state lasers would induce the formation of a plasma discharge at a targeted location in order to decompose greenhouse gases or replenish ozone in the region.

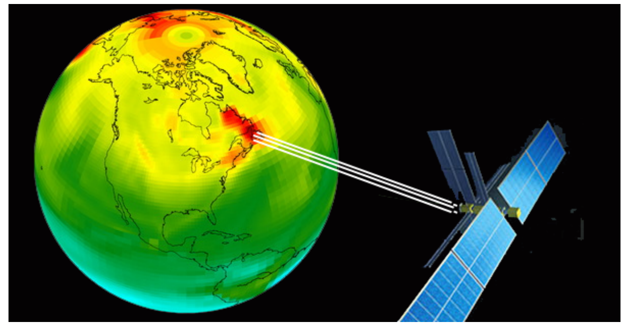

Fig. 1: SSP powered laser array targeting a region with a high concentration of atmospheric pollution in order to reduce the concentration via plasma decomposition.

II. PLASMA FILAMENTATION

Using this approach, the space based solar power plant will power an array of solid-state femtosecond pulse lasers (e.g. Nd-Yttrium Aluminium Garnet (YAG) pumped by a Ti-Sapphire amplification setup; 350 mJ pulse with 70 fs duration, $P_{peak} \sim 5$ TW) with the objective of producing a 'plasma filament' at a targeted region within the atmosphere. Plasma filamentation results from the nonlinear propagation of ultra short laser pulses within the atmosphere. The femtosecond laser pulses, emitted in the terawatt range, propagate through the atmosphere behaving as quasi solitons.

Due to the competing criteria of the focusing Kerr effect and the defocusing effect of the plasma on the laser beam, this results in the formation of a plasma filament with typical intensities of approximately $\sim 5 \times 10^{13}$ W/cm and electron densities of $10^{15} - 10^{16}$ cm^3. These filaments are also accompanied by strong, broad continuum of light emission, ranging from the UV to IR range (~230nm to 1400nm) [4, 5]. Depth control of the plasma filaments into the atmosphere would be provided by laser focus at the origin as well as the interaction of the filament with the increasingly dense atmosphere as it propagates from the upper atmosphere.

Fig. 2: Photograph of a terawatt femtosecond laser pulse directed into the sky from the University of Jena. The pulses form filaments of white light that can extend more than 20 km into the atmosphere [6]

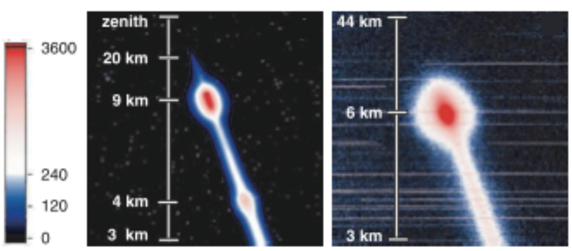

Fig. 3: Time lapse CCD images from same experiment showing the optical emission from the filament at ~20 km from the ground laser [7]

Ostensibly, existing research has focused on producing these filaments for studies involving remote sensing of pollutants and light detection and ranging (LIDAR) [7].

Most importantly to our concept, the concentrations of ozone were measured in the volume surrounding the filament; both by experiments in the atmosphere and in controlled lab conditions. Ozone concentrations were measured to be in the parts per million range (ppm) and were typically found to be between 100 and 1000 times higher then the background atmospheric measurement. This is a significant ozone generation mechanism, attributed to the excitation interaction of the plasma discharge and the atmospheric gases.

III. HIGH POWER RF INDUCED DISCHARGES

Atmospheric modification in order to regenerate ozone within the upper atmosphere could also be accomplished by using directed high power radio waves. Terrestrial experiments have shown that such an approach is feasible. Ozone concentration modification using high power RF was reported by Kulilov *et al* [8] at heights of between 22 to 60 km at the the Sura Ionospheric Heating Facility in Russia.

High altitude localized plasma discharges have also been widely reported in research carried out at the Ionosphere Research Institute in Alaska, whereby a large variable frequency array has been used to produce controllable aurora type plasma discharge events.

In addition, while there is no direct experiment carried out yet, it has been suggested that the interaction of high power RF could be used for environmental mitigation applications, whereby elements such as F, Cl and Br could be accelerated to the ionosphere/exosphere boundary and into interplanetary space in order to prevent them from degrading the ozone layer and remaining trapped as greenhouse gases.

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IV. OZONE LAYER REGENERATION & ATMOSPHERIC POLLUTION DECOMPOSITION

Conventional atmospheric theory states that the UV solar radiation is absorbed in stratosphere due to the chemical reactions of ozone formation. Figure 2 below illustrates the absorption process of UV A, B and C wavelengths as a function of Dobson Unit (DU) per kilometre versus altitude. The ozone layer can be depleted by the interaction of free radicals acting as catalysts in reactions which leads to ozone being chemically decomposed. Such free radicals include Nitrous Oxides (NO, N_2O) and hydroxyl groups (OH) as well as periodic group 9 elements (F, Cl, Br).

While natural sources for these elements and their respective compounds exist, their abundance within the atmosphere has increased markedly in recent years owing to their release from industrial and fossil fuel based systems. Consequently, the ozone layer has thinned or reduced beyond a point where the natural regenerative chemistry of ozone production can replace the losses. This has occurred most notably at the polar latitudes. As a consequence, unabsorbed UV radiation is able to reach the Earths surface, and these regions are colloquially known as ozone holes.

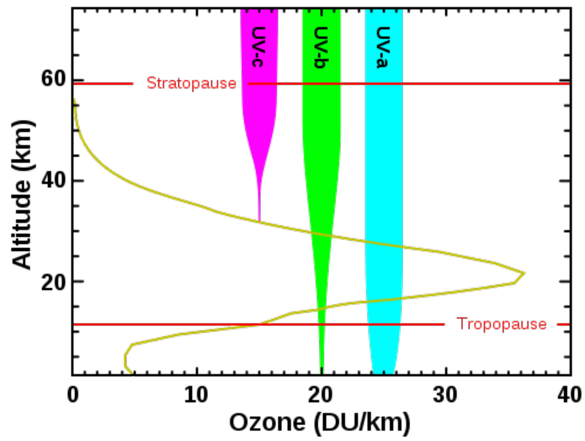

Fig. 4: Altitude for various levels of ozone and blocking of different bands of ultraviolet radiation.

Fig. 5: Plasma discharge at a specific altitude, induced by an orbiting SSP satellite using either laser induced filamentation or high power RF.

Using either the solid state laser or RF ionization methods, our approach would allow for substantially larger cross sections of atmosphere to be targeted then can currently be carried out via terrestrial based projects. Promisingly, it has been reported that for the laser induced plasma filaments, the yield of ozone creation was found to scale in an exponential manner with increasing laser fluence, as demonstrated by the cloud chamber experiments carried out by the DRACO laser of the Forschungszentrum Dresden-Rossendorf. The scaling up of this approach as a means of generating ozone and decomposing greenhouse gases is therefore possible, allowing for measurable effects on atmospheric composition over macroscopic volumes.

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V. APPLICATION TO SPACE SOLAR POWER

Our concept would readily integrate into existing proposals for SSP; the authors will defer on detailed cost assessments for the actual SSP setup as such reports have been carried out previously in some detail [9]. The costs for a space capable lasing system/high power RF antenna would be comparable to current systems on Earth multiplied by a scaling factor, representing the cost of producing such a subsystem suitable for operation in space. Considerations such as the weight of the setup (and cost to orbit and beyond), thermal management and effective lifetime would also have to be explored via further research and development.

As an example of integration of our idea with existing SSP proposed architectures we will refer to Carrington *et al* and their description for a modular deployment of a 100kW demonstrator system [10]. The modular approach for deploying 100kW satellites via Earth-to-orbit (ETO) suggested therein would allow for larger assemblies of identical laser beaming satellites to be deployed separately and assembled together in orbit, or form clusters of smaller satellites. Such satellites could conceivably carry two laser systems, or wireless power transmission/high power RF antennae; one system for power transfer to terrestrial commercial/national receiver stations, the other suitable for greenhouse gas/ozone regeneration purposes as proposed. Conceivably, a single laser system could carry out both functions, but this would require further research and development in the area of optoelectronics.

VI. I Pulse Laser Considerations

Previous discussions on using laser based SSP to beam power to terrestrial or lunar targets [11] have suggested that the lasing medium itself could be directly pumped by the incident solar energy, rather then being converted to electricity via photovoltaic cells and then conventionally electrically pumping the lasers. Such an approach would likely prove more efficient, however owing to the pulse times necessary to induce plasma filamentation, there may be issues in order to operate a laser within this regime. Using conventional electrical means to drive the laser action, with further study dedicated to producing a more efficient solar pumped setup, would best suit any initial trial of our concept in space.

A critical technical challenge that would need to be addressed would the efficient heat removal and overall laser diode array thermal management. Even with the high-energy conversion efficiencies available when utilising solid-state lasers, only part of the available solar energy collected would be used as laser output. The remaining energy would generate heat that would need to be dissipated from the diode array. Conventional satellite radiator systems, as well as novel architecture nanostructured radiator surfaces, could help alleviate this issue.

Finally, the effective lifetime of the diode array must also be considered. With aggressive usage of the system as well as its operation within a high radiation regime, it is likely that the lasing system would have a nominal effective lifespan before requiring repair or replacement.

V.II Earth Observation Systems (EOS)

Accurate measurement of greenhouse gas concentration and location volume is also a critical aspect of our concept. Fortunately, Earth observation satellite systems are already directly making such measurements and future missions will likely further enhance this means of atmospheric data acquisition. An interesting side application of using the solid-state laser approach described would be using the laser induced plasma filaments as a LIDAR detection system in and of itself or as a spectroscopic technique for 'depth profiling' the gas composition of the atmosphere.

Fig. 6: Some of the current NASA/National Earth observation systems missions.

V.I Technology Readiness Appraisal

In this section, we will briefly list the technology readiness of the critical technologies (table 2) using the ESA Advanced Studies and Technology Preparation Division criteria [12].

Technology Readiness Level	**Description**	**Concept Placement**
1	Basic principles observed and reported	Ozone Regeneration, Pollutant decomposition via Plasma
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	Solid State Lasing, High Power RF driven discharges
9	Actual system "Flight proven" through successful mission operations	Earth Observation Satellites, Photovoltaic Energy Systems, Thermal management systems

Table 2 – Technology readiness level for subsystems and concepts relating to our proposal.

Further fundamental studies of the base ionisation phenomena would also be recommended in order to deepen our understanding of the excitation and dissociation reactions that would take place between the plasma discharges and the atmosphere at stratosphere, mesosphere and ionosphere altitudes. These could be carried out via plasma particle-in-cell (PIC) computational simulations or in a broader context via simpler two dimensional 'global' model simulations. Such studies could be supported with experimental lab based low-pressure chamber experiments, similar to those carried out by the aforementioned DRACO laser.

V.II Ethical Concerns

The ethical considerations of our proposal must also be considered. A system as described within this paper could conceivably be used as a weapon, triggering potentially deleterious atmospheric changes over specific countries. International cooperation would therefore be required to ensure that this particular SSP application is used in the correct manner and adheres to current and future international space treaties.

CONCLUSIONS

In this paper we have proposed a conceptual system that could be used to regenerate ozone as well as decompose long-lived atmospheric greenhouse gases using the SSP approach to provide limitless, nearly emission free energy. We propose using directed atmospheric ionizing phenomena, such as laser induced plasma filamentation or high power RF waves, to generate localised plasma discharges within targeted regions of the atmosphere corresponding to areas of low ozone concentration or greenhouse gas concentrations, as determined by current or future Earth observation missions. The plasma discharge would generate ozone, via photoionization, excitation and dissociation of gaseous species within the targeted volume. These reactions would also result in the decomposition of long residence time atmospheric pollutants, mitigating their contribution to global warming.

On a much longer time scale, the approach we have presented could also be used to geoenginner the atmosphere of other planets such as Mars, as part of larger long-term terraforming initiatives.

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