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Solar Power Satellites for Clean Energy Enabled through Disruptive Technologies

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Abstract

The recent Paris Agreement of the UN Framework Convention on Climate Change of 2015 restricting global warming to a maximum of 1.5^{o}C represents a challenging task. In broad terms, it requires a massive reduction in carbon dioxide and other greenhouse gas emissions which implies a near-total elimination of fossil fuel combustion globally. Renewable sources of energy production – hydro, solar power, wind power, tidal/wave, geothermal and biomass – suffer from a variety of limitations (associated with poor base load power matching) requiring a variety of renewable sources portfolio mixes that vary with location. In addition, energy conserving efficiency increases must be implemented. Some strategies are drastic enough to affect our lifestyles and require widespread but unwelcome frugality (e.g. elimination of meat in our diets). There are a number of concerns with regard to the robustness and adequacy of such mixed portfolios, energy efficiency savings and other climate stabilization wedges. These scenarios ignore the marginality of renewables as they are based on projected energy demand based on population increases with increased standards of living capped at current developed world levels. There is little consideration of future energy consumption patterns induced by technological advance (e.g. ubiquitous computing), resource depletion (e.g. water desalination), and environmental side-effects (e.g. rare earth element extraction). We present an alternative scenario in which certain disruptive technologies in space technology can offer new energy options – solar power satellites - which are secure, scalable and environmentally safe. They can provide the current 20 TW global demand and they are readily scalable beyond this. The chief hindrance to date has been the high cost associated with rocket launches. New developments in a disruptive technology promises to remove this barrier – self-replication technology. Self-replication technology offers a means of bypassing launch costs through exponentially expanding productive capacity to leverage extraterrestrial resources. This self-replication technology is based on emerging 3D printing techniques in conjunction with extraterrestrial resource extraction. These technologies are crucial enabling technologies that promise the development of virgin infrastructure in space but also with significant impact on Earth – firstly, the provision of clean energy to Earth from space; secondly, self-replication technologies defeat investment discounting through exponential production; and thirdly, spin-off technologies that could revolutionise technological access in the developing world.

Keywords: global warming, solar energy, solar power satellites, geoengineering, self-replicating machines

1. INTRODUCTION

The prospect for global energy trends and its implications for climate change appear bleak. Current atmospheric CO$_2$ concentrations have surpassed 400 ppm. It is expected that once it reaches 450 ppm by around 2030, significant climatic effects will occur. Many consider the 450 ppm scenario assumption that global temperature rise will be limited to 2^{o}C to be too conservative and therefore dangerous. The recent Paris Agreement of the UN Framework Convention on Climate Change of 2015 to restrict global warming to a maximum of 1.5^{o}C stands in stark contrast to a recent Intergovernmental Panel on Climate Change (IPCC) prediction of an average of 4.0^{o}C (range of 2.4-6.4^{o}C) rise in temperature due to greenhouse house gas emissions. Although different studies of projected global energy needs vary in the details, there are some general trends upon which all are agreed [1]:

(i) Rate of global GDP growth is expected to average ~3%/year (2% in OECD countries and 4.5% in non-OECD countries)
(ii) Global population will reach 8-9 billion by 2030 from its current 7.3 billion (2015)
(iii) Non-OECD GDP to exceed OECD GDP by 2020 increasing to 125% by 2030
(iv) Global energy demand will increase by 35-50% from 2010 to 2035 reaching 35-40 TW

Demand for electrical energy is expected to be 80% higher in 2040 than in 2010. This is despite considerable efforts to enhance energy efficiencies to contain energy demands. Oil is expected to remain the primary energy source until 2030 (at a production rate of 100-110 million barrels per day due to enhanced oil recovery technology) primarily powered by non-OECD growth (60:40 ratio demand by 2030). Petroleum will still constitute 90% of transportation fuel in 2040 (1.6 billion road vehicles) compared with 95% in 2010 (800 million road vehicles). Coal is both abundant and cheap. Furthermore, coal demand in non-OECD countries – China, in particular – is expected to increase to 75% of its energy demand until 2020, thereafter decreasing. These scenarios however are projections based on population increases and standard of living enhancement to current developing country levels (to which Africa will not be privy). There is little consideration of future energy consumption patterns induced by technological advance (e.g. ubiquitous computing), resource depletion (e.g. water desalination), and environmental side-effects (e.g. rare earth element extraction). Such considerations will exacerbate energy demands. The only robust solution is to significantly reduce greenhouse gas emissions generated through fossil fuel combustion.

Solar power satellites (SPS), despite their promise as a clean energy source, have been relegated out of consideration due to their enormous cost and technological challenge. They are based on capturing solar energy from geostationary orbit and converting it into low-intensity microwaves for transmission to rectenna arrays on Earth. It has been suggested that for SPS to become economically feasible, launch costs must decrease from their current $20,000/kg to <$200/kg. Even with the advent of single-stage-to-orbit launchers which propose launch costs dropping to $2,000/kg, this will not be realized. Yet, the advantages of SPS are many. Here, a novel approach is presented to reduce the specific cost of solar power satellites to ~$1/kg by leveraging disruptive technologies – self-replication technology based on 3D printing and extraterrestrial resource utilisation. The use of extraterrestrial resources circumvents the requirement for launch by exploiting in-situ resources (specifically, on the Moon) to manufacture useful products. Self-replication technology enables us to focus on solving bite-sized technological problems on a local level which can be expanded globally without introducing scaling problems as each self-replicating unit is self-contained. The power of such technologies, self-replication technology in particular, will open up enormous possibilities for providing additional options for combating climate change whilst meeting increasing demands for global energy.

2. RENEWABLE SOURCES OF ENERGY

We very briefly consider some conventional sources of clean energy. Although there is a shift towards natural gas (growing at 1.3%/year expected to increase to 2.5%/y due to shale gas and coal-bed methane production) as a transition fuel towards renewables, it is still a fossil fuel that produces CO_2 at 45% the rate of coal combustion – given the need to curtail greenhouse gas emissions drastically and imminently, this is not a solution. The manufacture of synthetic fuel using biomass, despite being theoretically carbon neutral, competes with food production for agricultural land. Clean renewable hydroelectric power has reached capacity and is geographically restricted. It represents around 90% of current renewable energy capacity. Although nuclear energy is growing at 2%/year despite the Fukushima implications, it is expected that it will account for only 5-12% of global energy supply by 2030. The ultimate clean renewable energy source is the sun from which wind, tidal and biomass are derived. Wind, wave, tidal, solar and biomass will account for only 4% of global energy in 2030 with wind being the fastest growing at 8%/year. Their lack of scalability, intermittency and low returns are the primary barriers to use for base power (with the notable exception of nuclear energy which faces numerous political hurdles). They are typically assumed to be limited to 10-20% contributions to global electrical power sources. Hence, the projected energy mix in 2030 is expected to be approximately 25-30% oil, 20-30% coal, 20-30% gas, 5-10% nuclear and 10-20% renewables to meet an average energy growth of 40-50%. A typical example is the estimates by International Energy Agency (2011) of 27% oil, 24% coal, 23% gas, 8% nuclear and 18% renewable to meet a 36% energy growth in 2030. BP's 2012 figures are similar – 27% oil, 27% coal, 26% gas, 6% nuclear and 14% renewables to meet a 40% energy growth in 2030. It is apparent that renewables will be struggling to meet baseload power demands and will require significant backup power supplies provided through fossil fuel combustion. These estimates are extrapolations that take no account of increasing energy demand for new needs, e.g., the generation of hydrogen fuel from water rather than natural gas, or the generation of freshwater from saltwater in desalination plants to compensate for natural aquifers depletion, an increasingly alarming cause for concern.

3. SOLAR POWER SATELLITES

Solar power satellites (SPS) offer an additional option for a highly scalable, uninterrupted, clean source of baseload power to replace fossil fuels to dominate the global energy mix. The argument for SPS is simple - terrestrial solar power generates an average integrated solar energy density of around 65 W/m^2 compared with solar power satellites which can transmit 270 W/m^2 from space uninterrupted, all day, every day. At geosynchronous equatorial orbit (GEO) of 36,000 km altitude, SPS exploit the high areal density of solar energy in space of 1360 W/m^2 which is converted into electrical energy photovoltaically with a conversion efficiency of 20% or so depending on the solar cells used. This is then converted into microwave energy, most commonly proposed at 2.45 GHz (λ=122 mm), for transmission through the Earth's atmosphere with minimal attenuation to arrays of ground rectennas (rectifying antennas). The principle of such wireless microwave energy transmission has been demonstrated several times [2, 3]. Diffraction generates an angular spread given by:

$$\frac{d_t}{d_r} \approx R\lambda = 3.6\text{x}10^7 \times 0.122 = 4.4\text{x}10^6 \tag{1}$$

where d_t=transmitter diameter, d_r=receiver diameter, R=separation range, λ=microwave wavelength. Thus, it is easier to construct a large ground rectenna traded against a small space transmitter. Slotted waveguides for the rectenna are most commonly adopted for structural simplicity. On the ground, large arrays of rectennas convert microwave energy into direct current with a typical efficiency of 85%. They require no terrestrial power source. This simple construction with their passivity lends them to long lifetimes with a "green" pedigree. A commonly adopted limit to transmitted power is a maximum received peak intensity of 230 W/m^2 (23 mW/cm^2) at the rectenna centre with a 10 dB

Gaussian amplitude taper away from the centre of the rectenna centre. This is considered safe for humans and birds [4]. For comparison, around 300,000 birds are killed annually by wind turbines. There are however, more recent and stringent guidelines that restrict such microwave exposures but do not prevent passage through them [5, 6]. There are no adverse medical effects on humans subjected to low intensity microwaves. A retrodirective coded pilot signal from the receiver to the transmitter may be used as a reference signal to ensures transmitter pointing with high accuracy. There have been several architectural proposals for SPS but in all, each SPS satellite comprises three main parts:

(i) a large area solar energy collector nominally comprising panels of photovoltaic cells to convert sunlight into electrical energy – total area of typically ~10 km^2

(ii) a dc-to-microwave converter comprising semiconductor or microwave tube converters, e.g. klystrons or magnetrons

(iii) a transmitting microwave antenna to transmit ~GHz microwaves to ground rectenna arrays – total area of typically ~1-2 km^2.

The solar array is connected to the transmitter antenna via a motorised rotary joint. An integral phased array would eliminate the rotary joint [7]. A microwave tube such as a magnetron, klystron or travelling wave tube performs electrical dc to radiofrequency conversion with an efficiency of 50% typically. The 1979 NASA Reference System comprised a constellation of 60 SPS spacecraft in GEO to generate 300 GW of electrical energy to Earth. Expanding to today’s 20 TW (compared with 130 TW from global photosynthesis) requirement would require 4000 such SPS increasing to 6000 SPS by 2030 – this is an order of magnitude larger than the 600 geostationary satellites currently in orbit (only some of which are operational). If we assume that SPS supply only baseload power, these figures are reduced by approximately 40% to eliminate peak power loads to be supplied by terrestrial renewables. Japan’s SPS developments have proceeded the furthest [8]. The JAXA SPS 2000 design adopts a fully distributed formation flying system in which solar concentrators focus solar energy onto photovoltaic arrays. To exploit self-replication technology, we propose that an SPS concept of a distributed formation of 3×10^{11} 1m^2 micro-satellites to generate the 20 TW of energy required on Earth. Given a GEO ring with a perimeter of 2.65×10^8 m, this would effectively require a geostationary band 1.1 km wide representing a challenge for formation flying. This would subtend an angle that is an order of magnitude smaller than the resolution of the human eye, so would not be visible to the naked eye. Each satellite comprises a 1 m^2 cross section Fresnel lens concentrators for thermionic energy conversion for which we have conservatively assumed thermionic energy conversion efficiency of 10% and microwave conversion/transmission efficiency of 50%. Collectively, they may be phased to direct their microwave energy to any specified locations on the Earth’s surface.

4. SOLAR POWER SATELLITE PAYLOAD

One of the key technologies for the SPS is the energy chain from solar to microwave conversion. Although solid state radiofrequency amplifiers are under development, vacuum tube derived dc-to-rf microwave generators are superior in performance for both higher output power and superior efficiencies. Vacuum tube electronic devices include travelling wave tube amplifiers, extended interaction klystrons, backward-wave oscillator magnetrons, gyrotrons and free electron lasers [9]. All involve a hot cathode emitting electrons through thermionic emission accelerated by high voltage electrodes of ~10+ keV. The klystron is a linear beam amplifying vacuum tube based on a hot cathode generating an electron beam focused towards a positive anode within a glass tube accelerated by high voltage electrodes. The klystron operates at 300-500°C giving a converson efficiency of around 80-85%. A cavity magnetron is a high power vacuum tube that exploits E x B interaction generated by the passage of emitted electrons through a magnetic field. Rather than using electric fields to control the electron beam as in vacuum tubes, magnetic fields are used in the magnetron. They are suited to high power output ~MW but if precise frequency control is required, klystrons are preferable. Phase-controlled magnetrons offer the possibility of active phased arrays [10]. In order to prevent frequency excursions due to temperature variations, tuning with respect to a reference frequency is used to control frequency [11].

The klystron and magnetron are the key active components of the SPS payload: both have similar construction in being derived from vacuum tubes, and both are constructed from similar materials – this is of critical importance for extraterrestrial resource utilization and self-replication technology. Additional radiofrequency components required include a waveguide ferrite circulator to protect the microwave source from reflected power, tuner to match impedance between the microwave source and transmitting antenna, and a directional coupler to control signal propagation direction [12]. These complex vacuum tube structures lend themselves to 3D printing manufacture.

5. NOVEL SOLAR POWER CONVERSION

Most spacecraft are powered with arrays of photovoltaic cells to convert sunlight into electrical power. This represents the first stage of the SPS energy conversion process before conversion into microwave energy. If extraterrestrial resources are to be leveraged however, the use of solid state p-i-n structures based on doped semiconductors, dopants in particular, will be difficult – this eliminates solar photovoltaic conversion from consideration. It has become increasingly common to employ

Fresnel lenses or parabolic mirrors as solar concentrators to enhance solar cell performance [13]. Concentrators may be used to concentrate diffuse solar energy to a small point generating heat as a primary power source rather than light. This creates a solar furnace with temperatures as high as 2000-3000°C using concentration ratios of around 10,000. For example, a solar furnace comprising a 2 m diameter parabolic mirror with a focal length of 0.85 m can generate a solar illumination of 2 kW projecting an average flux of 15 MW/m^2 over an area 0.01 m diameter. This more than exceeds the heat input of around 10 MW/m^2 for the 2000°C temperatures required to melt refractory metal oxides. Hence, solar thermal energy is as viable an energy source as sunlight.

The second consideration then is to determine the conversion process from thermal into electrical energy. Spacecraft radioisotope thermoelectric generators (RTG) use thermoelectric conversion of radioactive decay heat into electrical energy using Si:Ge solid state converters [14]. Ge is rare on the lunar surface but Mg_2Si is an effective thermoelectric material. Both silicon and magnesium are available in olivine $(Mg,Fe)_2SiO_4$ minerals from which Mg_2Si may be extracted through the exothermic reaction of Mg and SiO_2 at elevated temperature. Thermoelectric energy conversion is however highly inefficient at 6%. The removal of thermoelectric material between the hot and cold electrodes reduces parasitic heat conduction suggesting that the thermionic effect may be exploited. The thermionic (cathode) element is a thin electric filament of tungsten (superior to most other candidate materials) in a vacuum within a glass tube, i.e. a vacuum tube [15]. A thermionic converter is a static device in which electrons are boiled from a hot cathode emitter to a cooler anode collector. Like dynamic energy converters, as the electron gas acts as a working fluid, the thermionic converter is subject to Carnot efficiency limits. The anode must be kept cool to avoid back-emission of electrons. This implies that the anode must be located a significant distance from and/or insulated from the heat source. Thermal radiators can be used for passive cooling. The anode electrodes are typically Ni with a work function of 5.0 eV. The higher the cathode temperature >1200°C, the higher is the thermal efficiency (nominally, 5-20%). High temperatures require a quartz tube. Efficiencies of 20% are typical of Russian nuclear reactor thermionic conversion with T_C=1650°C and T_A=650°C. This implies that the cathode must either be close to the heat source or linked to it through a highly-conductive thermally-insulated thermal strap. The tungsten filament is usually heated directly by an electric current passing through it. Thoriated tungsten filaments (impregnated with small amounts of thorium) exhibited very long lifetimes but are not essential. Alternatively, a nickel tube cathode may be indirectly heated by a separate interior hairpin tungsten heater element (separated from the cathode by a thin layer of ceramic insulation). Tungsten must be heated to 2200 K to yield an output current density of 25 mA/cm^2. An output of 1 A/cm^2 using W requires a temperature of 2600 K. Thermionic power generators tend to generate high current at low voltage requiring multiple converters for high voltage output. Thermionic conversion power density is typically ~1-10 W/cm^2, the upper value being typical of Russian nuclear reactor thermionic conversion. Problematic electronic space charging effects may be resolved without the use of Cs plasmas by shaping the electric potential applied through the thermionic converter thereby enhancing its efficiency [16]. A positive gate electrode is inserted between the emitter and collector electrodes to create a potential trough which accelerates electrons from the emitter but decelerates them towards the collector. An applied magnetic field guides electrons through holes in the gate electrode to enhance output current, similar to an ion engine. Conversion efficiencies may approach 40%. These complex structures lend themselves to 3D printing manufacture.

A second moderate temperature thermoelectric conversion stage may be serially added to a first stage thermionic emission system to enhance combined thermal-electric conversion efficiency to over 30% exceeding that from photovoltaic conversion [17]. Photon-enhanced thermionic emission (PETE) combines photovoltaic and thermionic conversion in a single process [18]. It involves thermionic emission of photo-excited electrons from a p-type semiconducting cathode at moderate temperature, i.e. PETE retains the structure of the thermionic converter but replaces the tungsten cathode with a p-type semiconductor. PETE exploits the photoelectric effect to enhance thermionic electron emission by elevating electron energy of semiconductors into the conduction band. It exploits combined photon energy and thermal energy to overcome the material bandgap. A caesiated GaN cathode at a temperature of 200^{o}C offers 50% conversion efficiency. Electric potential shaping can eliminate the Cs plasma requirement and Se may be employed as the p-type semiconductor for the cathode for a lunar-derived version.

SPS may exploit solar concentrators with thermionic arrays rather than photovoltaic arrays as their primary energy source. In SPS applications anyway, vacuum tubes are employed that operate through thermionic emission (be they klystrons or magnetrons). Conversion from solar concentrators to electrical energy requires temperature limits to be imposed by Ni electrodes to prevent melting beyond 1400^{o}C. Tungsten filaments may be heated directly using thermal energy from the solar concentrators however. This effectively converts thermal energy directly into microwave energy eliminating the electrical conversion step, thereby increasing efficiency further, but this has yet to be demonstrated. There is still the need however for electrical power for the klystron/magnetron electric/magnetic fields.

6. EXTRATERRESTRIAL RESOURCE UTILISATION

The cost of launch at ~$20,000/kg renders SPS prohibitively expensive. Studies have suggested that this must be reduced to <$200/kg for SPS to be viable economically. This cannot be achieved in the forseeable future – proposed single-stage-to-orbit launchers such as the Skylon spaceplane is estimated to reduce launch costs to ~$2000/kg. Similarly, SpaceX proposes to bring down the costs of launch close to $2000/kg with its Falcon Heavy launcher. Neither is adequate. It has been suggested that solar power satellites may be manufactured by space manufacturing facilities (SMF) at the Earth-Moon L4 or L5 libration points [19]. The raw materials from the Moon would be launched by electromagnetic launcher for processing at SMF. It would be more efficient however, to process lunar raw material on the surface of the Moon with the infrastructure located on the lunar surface.

The forthcoming Resource Prospector mission to the Moon (2018) will demonstrate many of the relevant extraterrestrial resource utilisation techniques required [20]. It comprises a lunar rover mounting a drill to acquire soil samples for analysis and a scientific package of experiments – RESOLVE (regolith and environment science and oxygen and lunar volatile extraction). Its primary mission is to demonstrate through stepped heating, the extraction of lunar volatiles from the soil and the extraction of iron and oxygen from lunar minerals. Of particular relevance here, is the extraction of iron as a base metal, carbon-based volatiles as feedstock for silicone plastics synthesis, and rutile as a ceramic. The processing of local lunar resources will require significant amounts of thermal energy – the power system proposed for SPS may be directly applied to a lunar power infrastructure. Although most energy requirements will be for thermal energy, electrical energy will also be required through thermionic conversion. A lunar solar furnace comprises a tungsten crucible to contain raw materials onto which parabolic mirrors or Fresnel lenses concentrate solar power generating temperatures up to 1600^{o}C or 2700^{o}C respectively. For mirrors, metals in general have high reflectivity. Steel can be polished to create ~75% reflectivity whereas nickel offers reflectivity ~80-85%. The solar furnace is capable of sintering regolith, smelting metal-containing minerals and/or vacuum pyrolysis [21]. Lunar anorthite may be heated into glass at 50-70 W/cm^2 for temperatures of 1700^{o}C with additional treatments [22, 23]. Precision glass moulding offers the prospect for complex lens geometries such as Fresnel lenses or other optical components without grinding or polishing. Precision glass moulding begins with a near-spherical glass blank inserted into a 3D printed precision mould of steel and heated to the working temperature between the transition temperature and glass softening temperature. The mould is closed and compressed under a controlled force imposed by motors. The glass is slowly cooled and removed from the mould. Convex shapes such as Fresnel lenses are readily moulded with surface roughness <3 μm. The active part of the power system comprises vacuum tube-based components constructed from glass casing enclosing nickel and tungsten electrodes in a vacuum.

7. THE PROMISE OF SELF-REPLICATION

It has been estimated that around 10,000 tonnes of equipment would need to be delivered to the Moon to build an industrial infrastructure of sufficient capacity to build SPS. This is also prohibitive. This problem can be overcome through the implementation of a self-replicating machine deployed onto the Moon to manufacture, using local lunar resources, the manufacturing capacity to build a distributed array of SPS systems. Self-replication is based on the concept of a universal constructor, a machine that can manufacture any machine (a construction-version of a Turing machine) given the appropriate program of instructions, raw materials and energy supply. Any machine includes a copy of itself, ie. a universal constructor is also a self-replicating machine. The self-replicating machine may be idealised as a robotic machine controlled by a computing machine, albeit complex in both cases. One of the simplest models of a (partially) self-replicating machine is the RepRap 3D printer [24], essentially a 3 degree of freedom cartesian robot that prints successive layers of plastic into 3D geometries including its own plastic parts. To complete the self-replication process, additional capacities are required: (i) 3D print metal components and structures (there exist a variety of metal 3D printing technologies such as electron beam freeform fabrication based on high voltage vacuum tubes [25]); (ii) 3D print its electric motors; (iii) 3D print its electronics and controllers; (iv) self-assemble its components (robotic manipulators which are kinematic configurations of motors would serve this function); (iv) additional manufacturing techniques such as milling and turning to provide fine manufacturing (which require motor drives); (v) transport mechanisms such as conveyors and vehicles (which require motor drives); (vi) chemical processing methods (which require motorised pumps and stirrers to drive chemical reaction throughput); (vii) mining techniques such as drills and excavators (based on motor drives); and (viii) energy generation and storage mechanisms (which may be implemented through thermionic conversion and motorised flywheels respectively). Hence, the ability to 3D print motors and electronic controllers would constitute an existence proof that self-replicating machines are feasible. Details on how in-situ resource utilization and self-replication may be achieved using 3D printing technology on the Moon have been detailed in [26, 27] with an emphasis on 3D printed motors and the principle of using vacuum tube-based neural networks for electronics. Vacuum tubes of course provide the basis for active electronics, thermionic conversion and electron beam freeform fabrication. Most of our efforts have been on 3D printed electric motors, the latest results of which we report here. We have successfully demonstrated a partially 3D printed DC motor. A magnetic core of 44% iron filings within a plastic matrix was manufactured from an NRCCan-patented powder metallurgy technique. A second version of the magnetic core of 25% iron filings within a plastic matrix was 3D printed from a commercially available feedstock. These cores were sandwiched with 3D printed end flanges around which was wrapped insulated copper wiring. The stators were constructed from plate aluminium and off-the-shelf magnets. This represents the first major step towards a 3D printed electric motor.

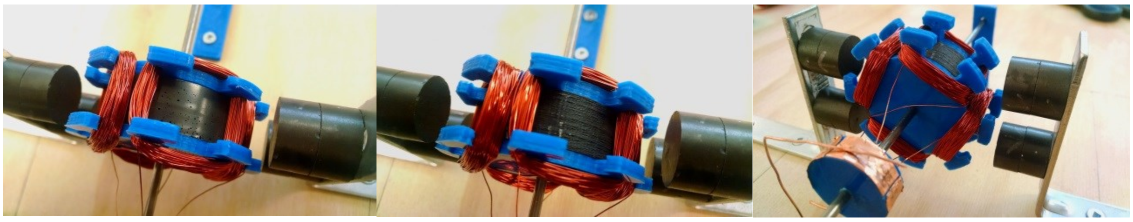

Fig. 1 3D printed motor prototypes: (a) core with 44% iron particles in plastic through powder metallurgy; (b) core with 25% iron particles in plastic through 3D printing; (c) complete configuration.

In terms of self-replicating architectures, the Chirikjian-Suthakorn lunar seed factory illustrates a self-replicating machine concept of 5 tonnes comprising two robots with a payload (comprising two manipulators, a bulldozer shovel, and material grinder/separator) with a total mass of 1500 kg including a 1000 kg furnace and 2,500 kg of solar array to cover 100 m^2 area [28]. The Chirikjian-Suthakorn Lego Mindstorms demonstration comprised a system of robots capable of assembling component modules into replicated robots. Though simple in scope and considered only assembly processes, this was a significant practical demonstration. Robotic assembly of multiple modules to form an integrated structure would represent an approach suited to the parallel facilities of self-replication. The SPS-alpha concept incorporates such robotic assembly of its thin-film reflector heliostat modules into an integrated satellite system [29]. In general, a self-replicating machine can construct any number of copies of itself extremely rapidly – its population grows as $\sim(x+1)^n$ where x=number of offspring per generation and n=generation number. Self-replication acts as an economic exponentiator. If a 1 tonne seed factory were launched to at a cost of $2B, the specific cost for 1.5 million copies in under 13 generations would have dropped from $2M/kg to only ~$1/kg. Once replicated, the machines may be re-programmed to manufacture the desired products in parallel, ie.

SPS. In this case, each of the 1.5M units of the self-replicating population could manufacture the required number of solar power satellite units.

8. CONCLUSIONS

The construction of SPS using lunar resources may be considered a derivative capability of self-replication technology. The elements required for self-replication are achievable. Self-replicating machines provide a mechanism to circumvent launch cost limitations by leveraging extraterrestrial resources through robotics. The keys to self-replication on the Moon are the capacity to build motors and electronics from lunar resources. Through self-replication technology, SPS becomes economically feasible, providing a powerful option for future scalable, reliable and clean energy. SPS can provide the full global energy demand of 20 TW and is expandable beyond this to accommodate much higher energy demands. There are three major implications. Firstly, this approach to baseload power generation involves no mining and manufacturing of terrestrial facilities, effectively relegating the entire energy generation industry off Earth away from the biosphere. Indeed, installation of SPS from the Moon rather than Eartth involves bypassing the LEO debris population thereby reducing the risk of worsening it. Furthermore, a population of SPS in GEO would favour the implementation of robotic on-orbit servicing [30] to service-tend the large SPS population and as a byproduct, perform active debris removal of larger debris such as upper rocket stages and defunct satellites to alleviate space debris [31]. Secondly, self-replication technologies defeat the age-old problem of NPV (net present value) discounting of technological investments [32]. The discount rate reduces the value of long-term future revenues by penalizing investment potential. Self-replication technology eliminates this by its exponential growth in productive capacity. This potentially may revolutionise how revenue streams may be computed. Thirdly, spin-off technologies from self-replication could revolutionise technological access in the developing world – a fully self-replicating machine offers productive access to effectively unlimited energy generation and product manufacture assuming access to the appropriate raw materials. A universal constructing machine capable of manufacturing copies of itself and *any other machine* in a very real sense cannot become obsolete.

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