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Summary of Frontier Energetics

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February 2022

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Introduction

Energy, supplied by the sun, is the basis of life on the planet and energy is the basis of human civilization. Humans added to nutritionally derived energy when they adopted fire, chemical combustion, and energy which could be created whenever and wherever needed. In the Industrial Age, fossil chemical energy sources such as coal, natural gas, and petroleum, were added to the energetics options and vastly increased human capabilities and impacts [ref. 1]. One of those impacts, unfortunately, has been climate change. More recently, nuclear has been added to the energy mix, providing some 20% of the electrical grid generation in the U.S. Energy is a sizable portion of GDP and is a key determiner of design for extant and projected capabilities such as agriculture, housing, manufacture, transportation, space faring, econometrics, and national security. There have been extensive efforts to ideate, discover, and develop alternative/improved energy sources and utilization approaches. These efforts have been greatly accelerated by climate change and the need to shift to renewable energy sources and away from fossil fuels for all applications [ref. 2].

Over the last decade, developments in economically viable renewable energy sources have been extraordinarily successful. The costs of renewable energy sources are still reducing rapidly, currently below those of fossil fuels, and their efficiencies are still improving [ref. 3]. Also, with the now rapid developments in space exploration, national security space, and commercial deep space there are serious needs to shift, given the importance of weight, from a dominant dependence on chemical energetics to others with greater energy density. Then there is the longer-term Earth warming issue based on the second law of thermodynamics, which considers the amount of waste heat rejected from human energetics that has to be radiated to space to maintain temperature stasis. Energy sources that are additional to natural ones (almost all of the natural ones are ultimately attributable to solar) including deep geothermal, nuclear, and fossil carbon, produce via the second law additional thermal waste that must be radiated away or warm the planet. The ongoing shifts to renewable energy would, along with energy conservation, greatly alleviate this future second law planet warming.

The purpose of this report is to summarize the frontiers of energetics, including generation, storage, regeneration/conversion, harvesting, and conservation. The generation discussion will include the renewables and the “exotics,” alternatives to fission/fusion based upon atomic/nuclear physics. Also discussed are high-energy-density chemical approaches. Overall, we have a surfeit of energy. The yearly renewables capacity of solar is 23,000 Terawatt years per year [TWy/y], while the current societal energy utilization is some 18.5 TWy/y [ref. 4]. An exotics approach proffers orders of magnitude greater energy density than fission/fusion. The technology readiness level [TRL] level for the frontier energetics archipelago varies from high for many of the renewables to very low for many of the exotics. Due to financial investments motivated by the low and decreasing costs of renewables, climate exigencies mandating a shift from fossil fuels to the renewables, and the increasingly rapid developments in near and deep space, research in these frontier energetics areas is accelerating, with in many cases major societal, econometric, and capability potential benefits.

Green Energy/Renewable Generation

There are a large number of renewable energy generation sources. The current dominant ones are solar photovoltaics (PV) and wind. Due to cost reductions/economies of scale/technology and efficiency improvements, their costs are now below the costs of nuclear and coal and dropping below gas. This cost reduction has resulted in some 90% of new electrical generation being renewables [ref. 3]. In fact, some 28% of the world’s electricity is produced by renewables [ref. 5] with this percentage climbing rapidly. There are now ongoing developments to convert many other energy-using and CO_2-producing activities to increasingly inexpensive renewable electricity. After much striving for many years via performance improvements to incrementally reduce CO_2 emissions of aircraft, the renewable electric cost reductions are shifting aircraft emission reduction efforts to solutions utilizing inexpensive renewable energy to produce hydrogen and hydrocarbons fashioned from water and captured CO_2, along with utilization of biofuels. These green fuels work well for aviation and have several benefits such as reduced aerosols. Green electricity will also charge batteries for electric ground transportation and aircraft, with ever increasing range as the batteries increase energy density from lithium ion through solid state/metal air to the performance of lithium air, at six times or more [6X plus] that of lithium ion. The green fuels can be utilized for fuel cells or Stirling cycle/turning generators to produce electricity for the electric motors, which are twice as efficient as gas turbine engines and are one of many advantages of going to electric propulsion [ref. 6].

The efficiency of solar PV has steadily improved. Laboratory research studied production of two electrons per photon, utilization of much more of the incident solar spectrum and regeneration of the heat losses, with mention made of potential efficiencies in the 70% plus range [ref. 7]. There is also research with regard to solar concentrator optimization for effectiveness and cost. Thin flexible PV films are under development which could be applied to transportation devices, buildings, etc. In the case of transportation, these films could be applied for partial recharge underway, extending range and enabling recharge while parked. The alternative solar energy approach is solar thermal, which is widely used to heat water as heat from concentrated solar is the desired result. Also, solar thermal innately provides stored energy as heat with longevity a function of what is heated. Thus far the costs of solar thermal are greater than PV and have in many cases different usage. The frontier issues for solar thermal include concentrator optimization, materials, material heated/storage, and efficient energy conversion from heat for many applications and cost requirements.

Then there is space solar power (SSP) - PV, or solar thermal lofted into space and beaming down energy via lasers or microwaves [ref. 8]. The draw for this is the greater solar intensity due to lack of clouds and the 24/7/365 availability. There are a bevy of reasons or issues that have delayed the exploitation of this renewable energy resource. These include major cost increases compared to terrestrial solar costs. SSP has been in a tail chase as the costs of the terrestrial options have plummeted. Other issues with SSP include lofting the huge equipage through the increasingly dense space debris, the pollution from the huge number of requisite launches and electromagnetic interference. Then there is the issue of the major latency to put SSP in place versus the exigencies of responding soon to now to climate issues. Space X reusable rockets engendered large space launch cost reductions that will reduce the costs of SSP significantly. However, with terrestrial PV cost in some markets falling through two cents per kilowatt hour heading to one cent and possibly less, and the storage costs dropping rapidly to compensate for the terrestrial solar variability, the initial applications of SSP will probably be either on other planets/moons or in niche, very high energy cost application areas on earth.

Hydro renewable energy provides most of the current pumped energy storage capacity. An Australian National University study of potential hydro pumped storage locations worldwide resulted in a very large number of such, some 530,000 sites [ref. 9]. Therefore, the current perception that hydro is largely built out is evidently not wholly correct. Thus far geothermal largely utilizes geyser/thermal fields on or near the surface of the Earth, notably in California, Iceland, etc. A Massachusetts Institute of Technology [MIT] study indicates that large areas of the globe are suitable for drilled geothermal energy extraction, depending upon depth drilled, with temperatures available from 200 degrees C at 2 km depth to 300 degrees C at 5 km depth. Estimates for the U.S. geothermal potential production indicates some 100 base-load gigawatts by 2050 [ref. 10]. Australia is particularly suitable for drilled geothermal, as are the western parts of the U.S. As petroleum and other drilled-for fossil resources are less utilized, some energy corporations owning a multiplicity of drillings are looking at utilizing them for geothermal energy generation.

As stated, wind along with PV are the largest and least expensive renewable generation approaches. There are three large wind resources. The one exploited most thus far is terrestrial wind, with the U.S. great plains a superb wind resource. The other wind resources are offshore wind and high-altitude jet stream wind [ref. 11]. The greatest source of jet stream wind on the planet is off the U.S. east coast, with a capacity estimated at some twice the U.S. installed grid load. The requisite lofted windmills are small due to the high wind velocities. The frontier involves siting, a place to run cables up to the windmill to position and extract the energy-thus far places where the Government owns the air space appear to be efficacious. Offshore wind is developing nicely now, especially off the U.K., where some are floating windmills. Huge rotors are being utilized to both improve efficiency/output and to reach greater wind velocities at higher elevations.

The renewable alternative to green H_2 and hydrocarbons for fuels is biofuels. Conventional biofuels are produced by freshwater plants called glycophytes, with attendant concerns regarding competition with agriculture/food production for fresh water and arable land and a consequent overall concern for capacity. The frontier here is salt plants or halophytes [ref. 12]. There are some 10,000 natural halophytes—plants that are tolerant to saline agricultural land and water. Many will grow reasonably well using direct seawater (no desalinization needed), even before we introduce advanced genomics. These plants could produce nearly all that glycophytes (freshwater plants) now produce. The immense advantages of switching to halophytes include:

- Saline-tolerant plant biomass uses what we have a surfeit of (and what could be our last major play regarding the ecosystem): wastelands, deserts (44% of the land area), and seawater (97% of the planet's water resources).

- Seawater contains 80% of the nutrients needed to grow plants, and researchers are developing new techniques to extract nitrogen from the air, thus requiring little fertilizer.
- Advanced technology is not required, and cultivation uses inexpensive land and water, so the economics are reasonable. The shift to halophytes could be accomplished in relatively short order.
- Halophyte cultivation for food would free up 70% or more of the freshwater we use for conventional glycophyte agriculture, and which we are now running out of for direct human use, thus solving both water and food problems.
- Cultivation of halophyte biomass would similarly obviate the use of arable land and freshwater for biofuels and provide petrochemical feedstocks for plastics and other industrial products. It is literally "green energy" and chemicals.
- Halophytes sequester up to 18% of their carbon dioxide uptake in their roots, removing CO_2 from the atmosphere.
- Seawater contains trace elements essential to healthy human physiology, which we have largely depleted from arable land due to overuse.

Cyanobacteria, seaweed, and algae represent another class of halophytes with potential for aquacultural development. Several of these produce excellent oils and protein and are far more productive than land-based plants. Through genetic engineering, aquacultural halophytes may have enormous productivity. The continent-sized nutrient stream that is the Mississippi River outflows into the Gulf of Mexico, which is now causing overly rich anoxic conditions, could possibly be used to foster aquaculture, thus reducing pumping costs, land taxes, and other costs. The worldwide capacity for aquaculture to replace freshwater use in producing food and biofuels—and provide sustenance to a much larger future human population—is massive. Overall, halophyte cultivation and development could address our interrelated land, water, food, energy, and climate problems, would provide society some breathing room and push Malthus [ref. 13] downstream by perhaps a century or more, thus alleviating many societal issues in a synergistic fashion.

Another set of renewable energy sources involves bodies of water including ocean waves, currents, temperature differentials and mixing fresh and salt water. The greatest opportunity in using these for large scale affordable generation is perhaps heat exchangers in the gulf stream near Virginia where there is cold water off to the side instead of at depth as in most Ocean Thermal Energy Conversion (OTEC) concepts. A systems study of such an approach indicated capacity similar to high altitude wind, some twice the U.S. installed grid load [ref. 14]. In northern Europe there are generation plants powered by mixing fresh and salt water, termed osmotic power [ref. 15], and where there are large tidal currents imbedded turbines have been used. Finally, there are biologics under development that produce hydrogen instead of oxygen.

Distributed Green Generation – The Rise of a Do-It-Yourself Mode of Living

Before the Industrial Age few people had "jobs," over 90% were farmers, living almost wholly in a do-it-yourself mode. The Industrial Age required factory workers which necessitated proximity to factories and the resulting requisite population density led to the expansion of cities/urban areas and later, the automobile-enabled suburbs. In that process, many lost the time and the land area for serious do-it-yourself living and associated independence. As we move out of the Industrial Age and into the Virtual Age, the technologies proffer a return to seriously effective do-it-yourself [DIY] independent living. With tele-everything, people can, and many now do, live wherever they want, including acreage on a mountain top, etc. The massive and ever-less expensive renewable energy developments are proffering distributed electricity generation and storage [ref. 16], obviating the need for wires to deliver electricity. The burgeoning electric Personal Air Vehicle developments proffer physical transportation without requiring road access to the homesite or fuels. With the Bio Revolution, it is possible to grow serious amounts of food on a small holding, water can be drilled for, captured from rain, recycled, etc., so folks could be off all the physical, electrical, road, and water grids. The development of massive numbers of low earth orbit [LEO] satellites to provide worldwide high-speed internet, with an emerging competition situation which should keep prices lowish, can provide superb communications for tele-everything without wires.

Development of the already large gig economy where employment is via the web, would add to the tele-work options in the rest of the economy. With tele-everything, we can do tele-education and tele-medicine, etc. as discussed. Then there is tele-manufacture or onsite printing. With carbon, hydrogen, and oxygen from onsite, we can make and print plastics. Printing is now being used to manufacture homes. Overall, there is a shift to independent, tele-everything, off all the physical grids and back to independent living that is enabled again by technology developments. If sizable, this shift would have truly massive econometric impacts on industrial agriculture, power companies, water companies, cell towers, ground transportation infrastructures as a whole, manufacture, education and with a shift to prevention, how we practice medicine. Such a shift to back-to-the-future independent DIY living would have massive favorable impacts upon climate, the ecosystem, and the economic 1% and 99% problem as the current econometrics associated with manufacturing, finance, fossil fuels, service industries, employment, etc. would be massively changed. We would have the option for nearly jobless independent living and mitigate greatly the impacts of the ongoing replacement of human labor by machines. Humans have twice before wholly changed their living and “working” arrangements, from hunter/gatherer to agriculture and agriculture to industrial. This high-tech enabled back-to-the-future, back-to-the-land option should be successful - if that is the way humans decide to live. The alternatives are interesting as we increasingly in the present econometrics milieu try to compete with the ever more intelligent machines, machines that can now ideate/create, the heretofore touted last bastion of human exclusivity.

Benefits of Renewable Energy Generation/Storage/Distributed Generation

The fundamental, nee essential benefits of renewable energy devolve from major reductions in the massive adverse climate change impacts via reductions in CO_2 emissions associated with energy generation and energy utilization in agriculture, manufacturing, and buildings. These climate impacts include flooding, storms, fires, rising sea levels, droughts, disease, heat/increased temperatures, and landslides. Going forward, renewable energy will reduce reliance on Middle East petroleum, favorably alter U.S. national security, result in a far more robust electrical grid capable of withstanding serious solar storms, enable nations to become their own “energy provider” with attendant econometric impacts, reduce water requirements for energy production, provide increased employment, and greatly reduce morbidity, some eight million persons per year, due to pollution from fossil fuels energy production [ref. 17].

Energy Storage

The usual energy storage modalities are variations of thermal, electrical, mechanical (i.e., pressure, springs, flywheels, gravity), and chemical. Due to the intermittency of solar PV and terrestrial/offshore wind energy, storage is required for them. The other renewables such as geothermal, high-altitude wind, hydro, solar thermal, biomass/biofuels, ocean sources, and osmotic power, are either base load or self-storing and do not require separate storage. One approach to variable renewables grid wise is interconnected grids that distribute energy from where there is solar or wind or other renewables, to where there is not. This has been successful in many instances. However, for the general case, given the increasingly vast applications of wind and solar PV for both local, distributed generation and central plants, thermal, electric, or other storage is required to replace fossil fuels. Such storage is becoming more available. In fact, PV plus storage is now deemed in many markets cheaper than a gas peaker plant [ref. 18] and grid storage costs have, as stated, decreased by 70% in the last three years. The spectrum of energy storage approaches is immense [ref. 19]. There are efforts for seasonal storage, usually via thermal storage, storing cold in the winter and heat in the summer. There are studies of using electric vehicle batteries as a collective storage option for the grid in the evening. There is increasing interest now in using green H_2 generated by inexpensive renewable energy to provide grid and other energy storage.

There are two general flavors of energy storage: weight sensitive and non-weight sensitive. The former pertains to transportation applications while the latter to fixed storage such as the grid. Weight sensitive storage includes batteries, fuel cells/green H_2, and green hydrocarbon storage. Weight insensitive storage subsumes compressed air, liquified air, batteries, flywheels, hydrogen generation and storage, atmospheric/other CO_2 to fuel, pumped hydro, superconducting magnetic energy storage, thermal batteries, molten salt, etc. Energy storage benefits include:

- Load leveling/peak shaving (~ 40% of cost from the 10% of peak hours)
- Frequency regulation
- Arbitrage
- Security/resiliency/reliability
- Distributed generation
- Electric transportation (land, sea, air)
- Controlling intermittency
- Reserve/backup/standby
- Enabler for the lowest cost renewables
- Replacement for “peaker” generation capacity

The nominal electric to electric storage efficiencies are [ref. 20]:

- Compressed air, 40% to 70%
- Pumped hydro, 70% to 85%
- Chemical batteries, 80% to 95%
- Hydrogen, 25% to 45%
- Flywheel, 70% to 95%
- Liquid Air, up to 70%
- SMES, 95%

Of these, hydrogen has the lowest efficiency, a consideration when using hydrogen for energy storage.

For heat storage, water is the standard with the frontiers being chemical structure, thermal storage, molten salt, zeolites, liquid metals, and white-hot silicon.

The frontier batteries include:

- Long duration (years) NASA nuclear thermionic avalanche cell [NTAC] nuclear battery, 22 KW/Kg of isotope
- Lithium metal, 500 WH/Kg
- Lithium air (6X plus Lithium ion)
- Solid State “glass” batteries
- Flow/reduction oxidation (fast recharge via replacement of materials)
- Fluoride ion
- Structural batteries (store electricity or H_2 in structure)
- Metal air batteries - Al, Li, Zn
- Semi-solid flow cell, pumped suspended solid particles, also vanadium and iron-chromium reduction-oxidation flow batteries, magnesium-ion batteries
- Sugar/enzyme, refillable/not rechargeable
- Solid electrolyte batteries (e.g., magnesium) also sodium air

Alternative Energy Generation/Storage Based on Nuclear Physics (aka “The Exotics”)

Beyond chemical energy lies the realm of nuclear physics. Since the middle of the last century, nuclear fission has been a major energy source with several issues including cost, safety, and radioactive waste. Even though fission nuclear is considered a renewable energy source in the sense it does not produce CO_2, it is losing out to other renewables due to cost. There are newer plant designs, but their projected cost is half of the current plants and that is still too high to be competitive with other options such as wind, solar, and storage. This section considers alternative atomic, molecular, nuclear-related alternatives for energy generation which are on the energetics frontiers and in most cases, at a low TRL.

Low Energy Nuclear Reactions (LENR)

Rediscovered in the late 1980’s [ref. 21] and dubbed “cold fusion,” what is now usually termed LENR or Low Energy Nuclear Reactions, was an experimental discovery with replication issues at the time and lacked an acceptable theory. Now, three decades of extant worldwide experiments [ref. 22] indicate something nuclear is present. However, there does not yet exist a cogent, verified theory and therefore LENR has been looked at with askance by the physics community. There are extant weak forces and other weak neutron-based theories (not “hot” fusion) involving surface plasmons, electroweak interactions explicable via plasmons on surfaces, collective effects, heavy electrons, ultraweak neutrons, utilizing neutron generation to obviate coulomb barrier issues. There are now many patents and LENR is beginning to evolve into the marketplace. Given a validated theory to engineer, scale, and to make safe LENR might constitute a major world energy revolution as a whole, with energy density levels compared to chemical observed thus far in the 10s to hundreds times and theoretical possibilities into the many thousands.

In the Widom-Larsen Theory [ref. 23], H_2 is adsorbed and “loaded” onto a metal surface and the resulting surface plasmon initiates collective effects. Some energy is added, and several types appear to work. From the LENR experiments and applicable related research, nano cracks/asperities in the surface morphology concentrate the applied energy and produce high localized voltage gradients. Such voltage gradients excite collective electrons to combine with protons in the surface plasmon to form an ultraweak neutron. These neutrons readily interact, producing neutron rich isotopes which undergo beta decay and transmutations. The heavy electron cloud converts the beta decay to heat, sans worrisome radiation and coulomb barrier issues, in agreement with experiment(s).

From experiments thus far, surface materials are required that adsorb large amounts of hydrogen (H_2 or D_2) such as Ni, palladium, etc. Once operating, internal infrared appears to be capable of replacing the input energy. The LENR process appears to occur on surfaces at nano morphology sites. Generic LENR "products" from experiments include heat, transmutations, and possibly some radiation, especially during startup or shutdown where there may be incomplete coverage of heavy electrons to accomplish conversion to heat (an engineering issue).

The three decades of experiments, lacking theoretical guidance, produced mostly low levels of heat. A few studies produced up to KWs. Several experienced runaway when they evidently got it more right, which may be a greater morphological population of nano scale sites. The experiments are now reproducible. From the three decades of hundreds of very detailed and careful experiments with redundant measurement approaches, positive results occurred over a relatively wide range of conditions/materials, and energy input approaches.

LENR is a non-obvious multistage process involving the weak force. Initial claims of "cold fusion" poisoned the well and LENR became the energetics third rail. There is also a lack of validated physics understanding and usually only low heat levels produced. There is also a dearth of experiments focused on validating (or not) theory, being mostly variations on previous experiments versus the basic physics and efforts to identify such. LENR is often considered simply too good to be true…incredulity.

From references 24 and 25, the LENR effect has been replicated hundreds of times using different materials and different methods of energy addition. Each method is found to produce energy well in excess of any plausible chemical source and correlated with identified nuclear products. LENR patent holders include: Airbus, Google, Leonardo, Brillouin, Mitsubishi Heavy Industries, Widom-Larsen, Boeing, MIT, and the U.S. Navy. LENR produces heat, which can be utilized directly or converted to electricity via such as Stirling Cycles, thermoelectrics, pyroelectrics, T-PV, etc. We went directly in the 1940s from chemical to strong force nuclear and in the process bought huge energy densities and huge radiation health/safety issues. We leapt over the weak force except for radiologics. With LENR we are apparently backtracking to the weak force.

The major issues going forward include development of a viable, proven theory to allow engineering, scaling, and safety. Given that, LENR could change climate/transportation/HVAC/manufacturing, energy costs overall, and in-space propulsion, habitats, In Situ Resource Utilization (ISRU), and on body transportation.

Nuclear Isomers

Metastable nuclear isomers are excited states of the nuclei that emit gamma radiation when de-excited. The emitted energy is stored in the excited state as shape or spin changes, with an energy density of emitted gamma energy on the order of E5 times chemical energy density, which is less than the E6 to E7 of fission/fusion. The half-life of these excited states varies from very short to extremely long. There are more than 100 isomers with a half-life greater than a week. The usual/natural decay rate for isomers provides (via utilization of the gamma energy as a heat source) some modicum of energy, but the engineering opportunity and challenge is to trigger serious gamma release as a function of energy load and requirements. Therefore, from a space operations standpoint, isomers could conceivably constitute an almost fission level controllable nuclear battery.

There are three major issues/problems/difficulties with isomer-powered nuclear batteries: the costs of production of the isomeric state, affordable, effective and controllable means to trigger the gamma release at the time and rate desired with a useful net positive energy production, and systems-engineering-level viable protection from gamma radiation at high keV to low MeV levels. All of these issues are under study but at the present time, the isomer approach for power and energy is at a very early research stage [refs. 26 and 27].

Positrons

Positrons are positive electrons and are the affordable anti-matter. Medical PET scans [positron emission tomography] utilize positrons. When the positrons annihilate with an electron, producing two prompt 511 keV gamma rays, there is a 100% mass to energy conversion. Therefore, their energy density is E9 times chemical or orders of magnitude more than fission/fusion, which involve fractional mass-energy conversion. There is no radioactive residue. It has the highest energy density source known and can be produced in accelerators, beta decay, and other methods/phenomena, including laser irradiation. The gamma produced can be used to heat tungsten, other materials, for propulsion, or employed directly for electricity production via photo electrics. The major issue with utilization of positrons for energy generation is positron storage. Positron storage approaches have included Penning traps and as positronium, an active area of research. Storage times on the order of 1000 minutes have been mentioned with projections for storage duration exceeding a year. The alternative to storage is to use suitable isotopes to generate positrons as needed, which is the approach for medical PET scans. Studies of positron powered thermal rockets indicate specific impulse [Isp] levels of 1,000 seconds, a bit greater than fission nuclear rockets at possibly reduced Kg/Kw (Alpha) [ref 28].

Atomic Fuels

Recombination of some atomic species, atoms into molecules, is a mono-propellant, with an energy density order of 20 times chemical. For example, storage of H (not H2) is possible either as metallic hydrogen or embedded in solid hydrogen (molecular hydrogen at 4 degrees K). It also provides a potential Isp for thermal rockets in the range of 1200 seconds. If utilized with an oxidizer, the Isp is reduced. Atomic boron and carbon provide Isp in the range of 700 seconds [refs 29 and 30]. The major issue with these atomic monopropellants is long-term storage.

Structural Bond Energy Release (SBER)

SBER is shorthand for Structural or Strain Bond Energy Release. Discovered originally by Bridgeman who used a combination of shear and compression to enable sugar and other hard-to-combust materials to explode. Gilman provided mechanochemistry as an explanation of the effects of shear and compression - the collapsing of electronic band gaps [ref. 31]. Engineering effects of such material processing includes cold, orders of magnitude more rapid chemistry, utilization as an initiator to combust materials not usually consider combustible (a superb “spark plug”) and energy storage. Research tasks to operationalize such capabilities include stabilization of treated, processed materials at ambient conditions and ensuring efficacious activation. It is of interest that application of shear and compression via collapsing band gaps produces electro-magnetic emissions which can be employed as non-destructive evaluation to detect cracking and earthquakes. SBER effects can be produced using lasers and sufficient processing can produce gamma and other radiation to possibly trigger nuclear processes (ref 32).

Fusion

For many decades now, fusion energy has been an unrealized energetics vision with regards to power and energy including space applications (especially propulsion) for which there exist a plethora of designs and alternatives. Compared to fission energy, fusion is much more difficult to achieve. Just how difficult is a function of the “fuels” employed. Also, compared to fission, fusion can have a somewhat greater energy density, different and usually lower radioactivity hazards, is less expensive, and utilizes more abundant fuel. A broad spectrum of approaches and fuel combinations have been conceptualized and studied over the years, including multitudinous fusion powered rocket designs. Thus far, fusion has not successfully produced a net positive energy output, even for terrestrial power where weight is not the serious issue it is in space. Anti-matter/positron power and energy is farther along than fusion and has orders of magnitude greater energy density. Currently, there are many terrestrial “mini” fusion concepts under study. Some of these utilize highly densified deuterium, which itself requires far more study. However, if such is as suitable as envisaged, it would greatly reduce the difficulty of establishing the conditions for fusion to occur. Key fusion space power and energy development issues include establishing and stabilizing the requisite conditions long enough for fusion to occur with net energy conversion, radiation related safety and overall weight, and efficiency/useful net positive energy [refs. 33 and 34].

Nuclear Batteries

There are recent developments in very different nuclear batteries with much greater energy production (up to some 22 kWs per kg of isotope) vs. usual nuclear batteries at 20 watts or less. For space flight where weight is critical, these have an alpha (total kgs per kW) of order one, vs. the alpha values of some 25 to 100s for fission reactors. The design scales from powering phones to tens of megawatts, with the far longer-term operability expected of nuclear vs. chemical batteries. These could power nearly everything in space including in-space and on-body habitats, ISRU, and on-body and in-space transportation. Estimates indicate they could power VASIMIR [Variable Specific Impulse Magnetoplasma Rocket], a high thrust magneto-hydrodynamic propulsion system with an Isp of some 6,000 seconds. This could enable a 200-day round trip to Mars, which would greatly alleviate in-space radiation and microgravity health concerns. Other potential utilizations include powering satellites, terrestrial and deep space mining, ships, manufacturing, and if using nuclear fission waste as fuel, reduceing the radioactivity in the process.

Cold, Fast Compression

Cold, fast compression is the formation of high energy density metastable quantum states in inner shell electrons via sudden compression at levels of 10-100 Mbar. These metastable states decay producing xrays with an energy density three orders of magnitude greater than chemical reactions.The approach is at low TRL, relatively expensive, and storage of the metastable states and their triggered release is forward work.

Alternative Chemical High Energy Density Materials

High energy density materials (HEDM) are nominally chemicals that have energetics exceeding hydrogen/oxygen via rapid exothermic decomposition [ref. 35]. Typically these materials are considered safety issues and consequently the typical TRL level of these materials is low. There are three prime uses for HEDM: explosives, batteries, and propulsion. Chemicals which have a greater energy density than hydrogen/oxygen (15.8 MJ/kg) include: Octaazacubane (N8, 22.9 MJ/kg), cubic gauche nitrogen (33 MJ/kg), lithium plus fluorine (23.75 MJ/kg), and beryllium plus oxygen (23.9 MJ/kg). Octaazacubane is considered an explosive but evidently has not yet developed as a fuel. Fluorine is extremely corrosive and reactive; beryllium is carcinogenic and a health hazard. These issues have reduced interest in them in despite of the potential increases in Isp of 50% to 100% compared to hydrogen/ oxygen fuel/oxidizer, values approaching nuclear thermal propulsion levels.

Energy Regeneration and Conversion

All energetics systems have losses, the amplitude of which is a function of specific design details, with the losses usually occurring as heat. This heat is normally dissipated using radiators, heat exchangers, cooling towers, etc. In the design of many systems there have been efforts to regenerate energy and reuse these losses, notably in auto braking, trains, wind turbines, elevators, buses, cranes, robotics, power plants, photo voltaics, fuel cells, etc. [ref. 36]. The components of an energy regeneration system include energy extraction and transmission and depending upon the details of the reuse approach storage conversion and utilization.

In space faring systems, weight is always a serious issue or metric. Many to most current space systems do not employ regeneration, leading to larger size/weight/cost energy generation and heat dissipation systems. These overall system components could possibly be smaller/lighter/less expensive with the systems tradeoffs being the added weight/cost and size of the requisite regeneration components. Particular space-energetics related systems with potential regeneration net favorable impacts include nuclear reactors, batteries, PV, lasers, and others that generate heat that has to be dissipated, which in space means radiation to space.

Approaches to optimize regeneration and energy generation/loss dissipation include:

For dissipation:

JHeat exchangers with riblet surfaces, greater heat transfer per unit of pumping power [ref. 37]

- Liquid droplet radiators/belt radiators, major size/weight reductions [ref. 38]

For conversion:

- High efficiency thermal electrics [T-E]
- High efficiency thermal photovoltaics [T-PV]
- High efficiency thermionics

What is apparently needed are systems studies of various combinations of regenerative system piece parts. These studies would be for one or several onboard, on-body energetics sources/utilizations that might benefit from regeneration, be potentially downsized, including source/radiator size with the metrics of overall cost, safety, reliability, size, and weight. This will determine the efficacy and benefits of increased utilization of regeneration in space.

Energy Conversion

Optimal utilization of power and energy usually requires energy conversion processes, wherein energy is converted from one form to another more useful form. The most common conversion desired is heat into electricity such as for nuclear fission reactors, which produce heat, requiring conversion into electricity for most applications. There are many extant conversion approaches that are efficacious for various system design instantiations. Generation approach and usage is a system and system of systems level optimization issue concerning cost, weight, size, efficiency, robustness, temperature levels, materials, and safety. The extant energy conversion options for space applications with their peak level efficiency include (ref. 39):

- Thermal electrics, utilizing spatial temperature gradients, some 5% to 20% efficiency
- Piezo-electrics, utilizing mechanical movements, heat is not directly involved, efficiency up to 80%
- Thermal photovoltaics, utilizing radiated IR, up to 60% efficiency
- Pyro-electrics, utilizing temporal temperature changes, up to 90% of Carnot efficiency
- Thermodynamic cycles, such as Stirling or Brayton, utilizing rotation to turn electric generators, 40% efficiency
- Fuel cells, convert chemical energy to electricity, 80% efficient
- Solar cells/photovoltaics, convert photons to electricity, efficiency to 50%

Higher system conversion efficiencies have been and can be operationally obtained by combining several conversion processes including converting the heat produced via PV solar cells. These conversion approaches are utilized in energy regeneration as well as for primary usage. All of these conversion approaches have individual optimization conditions, and are subjects of ongoing research. They are also recipients of benefits from ongoing miniaturization and materials technologies and are applied across the spectrum of non-aerospace domestic and industrial requirements. Particularly interesting current research developments in energy conversion for PV include two electrons per photon and utilization of much more of the incident photon spectrum. Then there is the recent Sang Choi invention of a new approach to T-E conversion, with efficiencies predicted to be above 20% [ref.40].

Energy Harvesting

Energy harvesting, at one time termed energy scavenging, is energy generation using local or ambient energy sources. It can also be considered a form of regeneration [refs. 41 to 43]. The usual application of energy harvesting is for powering the increasingly miniaturized, reducing required operating power, sensors, and IT devices. However, it could also be considered for local and at home use distributed generation given sufficient ambient energy levels such as is available from solar. As required IT device and sensor operational power levels have reduced, the interest in energy harvesting has greatly expanded. In fact, there is a very sizable amount of literature published and a significant number of commercial harvesting devices available for almost all energy sources. Prime applications include mobile phones, sensor networks, national security usage, medical and health care sensors, implants, and consumer goods. The potential energy sources to be harvested are legion. They vary in strength from microwatts to milliwatts or more and utilize many energy conversion approaches. They include: photons/solar, thermal, wind, chemical, salinity gradients, kinetic energy including acoustics, vibrations, fluid motions, ambient electromagnetic /radio frequency [EM/RF], chemical "fuels," phase change and gravity. Some sources are human generated, some machine, some ambient, and can be situated inside or outdoors. The global energy harvesting industry is some $500 M/year, growing at 10%/year. A short listing of some ambient energy harvesting sources include: heel strike, body heat/motions, auto passage, PV on roads, raindrops, back yard streams, micro wind, ambient RF, the 100V D.C./vertical meter electric field in the atmosphere near the surface, ground heat pumps, road heating, arm/hand movements, thermal sources, tree movements, furnaces, combustion engines, cooling towers, mouse button clicks, and helicopter and train vibration.

Energy Efficiency

The major cause of the now decade long decline in energy use per person appears to be primarily energy conservation [ref. 44 to 46]. The nominal definition of energy conservation is approaches to reduce the use of energy, either by using less or increasing energy efficiency, enabling similar results with less energy. The foremost organization ideating and advocating energy conservation, which they term "negawatts," is the Rocky Mountain Institute. The nominal expected impacts of energy conservation upon energy usage going forward is some 44% by 2040, and 50% to 60% by 2050. These are obviously large percentages with major econometric and climate impacts. There are nominally four major sources of energy use/loss: electricity generation, transportation, manufacturing, and buildings/agriculture.

Conservation associated with electricity generation from renewables includes increases in PV, other renewables efficiencies, and the efficiencies of energy conversion approaches and storage. Buildings utilize energy for heating, ventilation and air conditioning [HVAC], lighting, appliances, and electronics. Conservation approaches include insulation, smart meters, occupancy sensors, passive solar, heat pumps, shelter belts, and light-emitting diode [IED] lighting, along with regeneration from waste heat including dryer venting and ventilation air flows. Then there are the major improvements (some 30%) in the efficiency of electric motors, which, overall are responsible for some 50% of all electricity use. The frontier for such would be room temperature superconducting materials to obviate much of the electrical losses. Conservation and distributed generation have advanced to the point where buildings can now generate instead of use energy, which will enable a major increase in rate of the growth of renewables and a reduction in the overall amount of such growth necessary for the humans on the planet to go "green."

Transportation is now shifting from heavy transportation fuels to electrics, and electric motors are twice as efficient as combustion engines. A major source of transportation energy use reduction is the societal shift to tele-everything including tele work, travel, shopping (reduces CO_2 emissions by 15X compared to physical shopping), medical, education, commerce, socialization, etc. Reducing physical in favor of virtual travel, digital reality, results in major energy savings. There is a perceptible shift to more walking and bicycling. Also, there is regenerative braking and serious drag reduction. As an example, drag reduction for trucks can include small TV cameras/monitors vs. the large external mirrors, front/side air dams, flush wheel covers, and smart tires to reduce rolling friction and turning vanes at the rear to fill in the base region. A general energy conservation approach for transportation is weight reduction via structural design and frontier materials. It is now possible to nano print materials with much better microstructure, resulting in large improvements in material properties. Another overall transportation energy conservation approach is the development of home printing manufacturing, which would reduce the amount of tonnage that is needed for transportation. In water, parts per million of high molecular weight polymer can reduce turbulent skin friction drag, a large percentage of ship drag. A large drag reduction could be obtained if the phyto and zoo plankton were sieved out of the cooling water and cultured into a polymer for injection over the hull. For aircraft, large drag reduction is available through use of externally truss-braced wings which enable large spans for drag due to lift reduction and wing designs for laminar flow.

Opportunities for energy conservation in manufacturing include: going to autonomous robotic “dark factories,” advanced low energy use electric motors, regeneration of waste heat from manufacturing processes and co-generation of heat and electricity, replacement of process combustion heat requirements with electrics that are less expensive and provides energy conservation, low pressure drop membranes, and improved fluid flows/reduced pressure drop throughout.

Concluding Remarks

Energetics is now one of several ongoing technology revolutions that, collectively and singularly, are greatly changing society and econometrics. The litany of these tech revolutions includes IT, bio, nano, quantum, and energetics. This report examines the frontiers of the energetics technology revolution. The exigencies of climate change, due to the associated now obvious massive climate change impacts, is producing a wholly new renewables-based energy system, whose development is greatly accelerated by rapidly reducing costs for both generation and storage. The utilization of low-cost renewable energy generation and storage for transportation, buildings, agriculture, and manufacturing will go far to reducing CO_2 emissions and costs. There are technical approaches for large further improvements in the efficiencies of renewable energy and storage approaches, major cost reductions, and huge untapped alternative green energy sources.

Especially for applications to the burgeoning space industry, there are several nascent atomic/nuclear energy sources currently at lower TRL that could revolutionize space access, operations, and colonization. They include positrons, a nuclear battery proffering some 22 KWs/kg of isotope, atomic fuels, and once the physics is proven to enable engineering, scaling ,and making safe, possibly LENR. The key to affordable space development and space faring is energetics. The ongoing miniaturization of sensors and IT devices with corresponding reduced energy requirements have fostered an expanding and increasingly applied technology for ambient energy harvesting. Energy conservation, including regeneration of waste heat is reducing overall energy use, with a projection of up to 60% effectiveness, This is a huge number with equally huge econometric and climate benefits.

Frontier energy approaches with the greatest impacts include halophytes, which are salt plants grown on wastelands (44% of the land) using saline or seawater (97% of the water on Earth) for food, water, biomass for chemical feed stock, biofuels, CO_2 sequestration, and land. Another is the continued increase in PV efficiency into the 70% range via two electrons/photon, utilization of more of the solar energy spectrum, and regeneration of the heat produced. These, along with continued materials developments and manufacturing efficiencies, are slated to reduce electricity cost below one cent/kWh, enabling much greater electric utilization for climate and overall widespread cost reductions in the economy. Equally to more important in terms of overall impact on energy utilization, is the entire panoply of conservation approaches, including at the systems level. The capacity of renewables, including several as yet untapped sources, is a huge multiple of current and projected energy utilization.

References

1. EIA, “What is energy? Sources of Energy,” https://www.eia.gov/energyexplained/what-is-energy/sources-of-energy.php
2. Long, Noah and Steinberger, Kevin, “Renewable Energy is Key to Fighting Climate Change,” NRDC, July 26, 2016, https://www.nrdc.org/experts/noah-long/renewable-energy-key-fighting-climate-change#:~:text=What's%20more%2C%20renewable%20technologies%20can,no%20signs%20of%20slowing%20down.
3. Roser, Max, “Explained: Why Renewables Became So Cheap So Fast,” World Economic Forum, 4 Dec. 2020, https://www.weforum.org/agenda/2020/12/renewables-energy-price-cost-cheap-climate-change-sustainability/?utm_source=sfmc
4. Nussey, Bill, “The Earth Gets More Solar Energy in One Hour Than The Entire World Uses In A Year,” The Freeing Energy Project, 7 July 2019, https://www.freeingenergy.com/the-earth-gets-more-solar-energy-in-one-hour-than-the-entire-world-uses-in-a-year/
5. EIA, “Global Energy Review, 2020,” April 2020, https://www.iea.org/reports/global-energy-review-2020/renewables
6. Bushnell, Dennis M. “Enabling Electric Aircraft Applications and Approaches,” NASA/TM – 2018-220088, 2018
7. Chandler, David L. “Experiments Show Dramatic Increase In Solar Cell Output,” MIT News, July 3, 2019, https://news.mit.edu/2019/increase-solar-cell-output-photon-2-electron-0703
8. Mankins, John, “The Case for Space Solar Power,” Virginia Edition Publishers, Jan. 2014
9. Australian National University, “ANU Finds 530,000 Potential Pumped-Hydro Sites Worldwide,” 1 April. 2019, https://www.anu.edu.au/news/all-news/anu-finds-530000-potential-pumped-hydro-sites-worldwide
10. Tester, Jefferson W., “The Future of Geothermal Energy,” INL Report INL/EXT-06-11746, Nov. 2006, https://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf
11. Blackman, Christine, “High Altitude Wind: The Greatest Source of Concentrated Energy on Earth,” Stanford Report, June 23, 2009, https://news.stanford.edu/news/2009/june24/high-altitude-winds-062309.html
12. Sharma, Rita, “Halophytes as Bioenergy Crops,” Frontiers in Plant Science, 2016, 7, 1372
13. Thomas Robert Malthus, “An Essay on the Principle of Population,” printed for J. Johnson in St. Paul's Churchyard, 1798.
14. Mcgowan, J.G. and Heronemus, W.E., “Gulf-Stream-Based Ocean Thermal Power Plants,” J. Hydrodynamics, 1976, V. 10, No. 2, pp. 33-38
15. Wikipedia, “Osmotic Power,” https://en.wikipedia.org/wiki/Osmotic_power
16. St. John, Jeff, “5 Major Trends Driving The $110B U.S. Distributed Energy Resources Market Through 2025” Green Tech Media, June 22, 2020, https://www.greentechmedia.com/articles/read/5-takeaways-on-the-future-of-the-u.s-distributed-energy-resources-market
17. Mittelman, Elisheva, “Air Pollution from Fossil Fuels Costs $8 Billion Per Day, New Research Shows,” Yale Environment 360, E360 Digest, Feb. 12, 2020, https://e360.yale.edu/digest/air-pollution-from-fossil-fuels-costs-8-billion-per-day-new-research-finds
18. James, Shayna, "Solar Plus Storage is Displacing Natural Gas Peaker Plants,” Nuvation Energy, Sept. 8, 2020, https://www.nuvationenergy.com/resources/article/solar-plus-storage-displacing-natural-gas-peaker-plants
19. DOE, “Technology Assessments, Electrical Energy Storage,” Quadrennial Technology Review, 2015, https://www.energy.gov/sites/prod/files/2015/09/f26/QTR2015-3C-Electric-Energy-Storage.pdf

20. EESI, “Fact Sheet: Energy Storage [2019],” Feb. 22, 2019, Environmental and Energy Study Institute, https://www.eesi.org/papers/view/energy-storage-2019
21. Krivit. Steven B. and Ravnitzky, Michael J., “It’s not Cold Fusion, But It’s Something,” 7 Dec. 2016, Scientific American Guest Blog, https://blogs.scientificamerican.com/guest-blog/its-not-cold-fusion-but-its-something/
22. LENR-CANR.Org, A library of LENR Material, https://lenr-canr.org/
23. Widom, A. and Larsen, L., “Ultra Low Momentum Neutron Catalyzed Nuclear Reactions on Metallic Hydride Surfaces,” The European Physics Journal C, Particles and Fields, April 2006, V. 46, Issue 1, pp. 107-11
24. Storms, Edmund, “The Science of Low Energy Nuclear Reaction,” World Scientific, 2007
25. Storms, Edmund, “The Explanation of Low Energy Nuclear Reaction,” Infinite Energy Press, 2014
26. Hartouni, Edward P., “An Assessment of Nuclear Isomers as an Energy Storage Medium,” CP 1103, Space, Propulsion and Energy Sciences International Forum – SPESIF-2009, Edited by G.A. Robertson, American Institute of Physics, pgs. 492-500.
27. Carroll, James J., “Ups and Downs of Nuclear Isomers,” Physics Today, v. 58, Issue 6, 39, 2005
28. Smith, Gerald A., “Positron Propelled and Powered Space Transport Vehicle for Planetary Missions,” NASA NIAC Phase 1 Final Report, 2006, http://www.niac.usra.edu/files/studies/final_report/1147Smith.pdf
29. Silvera, Isaac F. and Cole, John W., “Metallic Hydrogen: The Most Powerful Rocket Fuel Yet to Exist,” Journal of Physics, Conference Series215 [2010] https://iopscience.iop.org/article/10.1088/1742-6596/215/1/012194/pdf
30. Palaszewski, Bryan, “Solid Hydrogen Experiments For Atomic Propellants,” NASA /TM-2001-211292, 2001
31. Gilman, John J., “Mechanochemistry”, Science, V. 274, 4 Oct. 1996, P. 65
32. Gilman, J.J. “Mechanisms of Shear-Induced Solid-State Reactions,” Solid-State Chemistry of Inorganic Solids. Materials Research Society, Symposium Proceedings Volume 453, Davies et al Editors, 1997, pgs. 227-232
33. Andersson, Patrik U. and Holmid, Leif, “Ultra-Dense Deuterium: A Possible Nuclear Fuel for Inertia Confinement Fusion [ICF],” Physics Letters A, V. 373, Issue 34, 17 August 2009, pg. 3067-3070
34. Winterberg, F., “Advanced Deuterium Fusion Rocket Propulsion For Manned Deep Space Missions,” JBIS, Vil. 62, pp. 386-401, 2009
35. Liu, JPING, et al., “Development of High-Energy-Density Materials,” Science China Technological Sciences, 63, 195-213, 2020
36. Jouhara, Hassan, “Waste Heat Recovery Technologies and Applications,” Thermal Science and Engineering Progress, V. 6, June 2028, pp. 268-289
37. Choi, K.S., “Breakdown of the Reynolds Analogy Over Drag Reducing Riblet Surface,” Applied Scientific Research, 51, 149-154, 1993
38. Mattick, A.T. and Hertzberg, A., “The Liquid Droplet Radiator – An Ultra-Light Heat Rejection System for Efficient Energy Conversion in Space,” Acta Astronautica, V. 9, Issue 3, March 1982, pp. 165-172
39. Wikipedia, “Energy Conversion Efficiency,” https://en.wikipedia.org/wiki/Energy_conversion_efficiency
40. Choi, S.H., Kim, H.J., Duzik, A.J., and Park, C., “Metallic Junction Thermoelectric Generator”, U.S. Patent No. 11,063,198, July 13, 2021.
41. Janek, L. and Singule, V., “Energy Harvesting For Aerospace; Application Possibilities,” Mechatronika, 2014, Brno 2014, pp. 183-187
42. Bizon, N. et al., “Energy Harvesting and Energy Efficiency,” Springer Lecture Notes in Energy, 2017

43. Akinaga, Hiroyuki, “Recent Advances and Frontier Prospects in Energy Harvesting Technologies,” Japanese J. of Applied Physics, V. 59, N-11, Oct. 2020
44. Siegel, R.P., “The Infinitely Expandable Resource,” Mechanical Engineering, Aug. 2020, pp 46 – 50
45. Lovins, Amory, “How Big is The Energy Efficiency Resource?,” Environmental Research Letters, 13, 18 Sept. 2018
46. Environment America, “The Cleanest Energy: Conservation and Efficiency,” https://environmentamerica.org/feature/ame/cleanest-energy-conservation-efficiency