NASA/TM–20220014816

Distributed Energy Generation Including Space Applications

Dennis M. Bushnell
Langley Research Center, Hampton, Virginia

November 2022

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Introduction

Before the 1900s, energy generation was local or at the point of use. The advent of electricity in the early 1900s, with the concomitant opportunity to transfer large amounts of energy over long distances on small wires, produced a dominant paradigm of centralized energy generation and a large, complex, electrical transmission grid [ref. 1]. The major response to reducing carbon dioxide (CO_2) emissions for climate change mitigation is scalable renewable energy sources. Along with their plethora of benefits, they are now shifting energy generation “back to the future,” or back to point of use generation (termed distributed energy generation (DEG) or distributed energy resources (DER)) [ref. 2]. This shift is altering the industrial, centralized energy generation and distribution landscape. The initial substantive instantiations of DEG were to “microgrids, regional-to-localized applications” while keeping connections to the larger grid to both add and extract energy as needed, a capability termed smart grids. However, DEG for individual holdings is now developing rapidly. This DEG revolution in energy is increasingly enabled by the massive cost reductions of such as photovoltaics (PV), wind, and other scalable renewable generation approaches, and the now major cost reductions in energy storage [ref. 3]. DEG combined with serious conservation and storage works in northern latitudes [ref. 4]. The overall benefits of DEG are large. There are some 180,000 off-grid homes in the U.S. [ref. 5], and assertions that “off-grid power will be our new norm” [ref. 6]. California mandates that new residential home construction must include solar panels [ref. 7]. PV cost has dropped 89% over the last 10 years [ref. 8]. The localized home utilization of DEG and storage is increasingly effective and compact with an emerging eye to external cosmetics, strong growth projections, significant increases in efficiency, and further cost reductions. In Germany now, approximately 50% of new PV installations include onsite storage [ref. 9]. The projected compound annual growth rate (CAGR) for DEG during the 2020s is 14%, with a market of over $900 Billion worldwide [ref. 10]. The centralized energy generation and grid distribution industry is accommodating this DEG shift by reducing generation levels and via smart grids adding and utilizing excess energy produced at DEG sites and, going forward, treating electric vehicles as available energy storage. This is having the effect of increasing the grid cost vice the alternative of reducing or eventually perhaps eliminating it. The energy generation companies, while generating less energy than otherwise required, accrue income from the smart grid. As distributed storage and renewable generation costs continue to drop and serious conservation occurs, the central grid could conceivably atrophy. DEG has always been the preferred energetics approach to space faring, with advanced scalable, light weight, high energy density nuclear batteries proffering a revolutionary DEG improvement across the space application energy spectrum. Space-applicable on-body centralized energetics approaches under development, approaches necessary due to lack of scalable DEG energy sources, include space solar power with beamed energy and a centralized fission nuclear reactor on the Moon, with cable distribution to several energy utilization sites/utilizations. The military is increasingly interested in renewable DEG for both climate mitigation and as an alternative to moving heavy expensive fossil fuels.

DEG Energy Sources

The increasingly inexpensive costs of renewable green electricity, along with the improved efficiency of electrics, is fostering a switch from fossil fuels to electricity for transportation, manufacturing, buildings, and agriculture, the other major sources of CO_2 [ref. 3]. If green fuels such as green hydrogen or hydrocarbons are required, there are approaches using electricity which can produce them. There are a large number of renewable energy generation sources that produce electricity [refs. 3 and 11]. The current dominant electrical generation sources for DEG are solar photovoltaics (PV) and wind. Due to cost reductions, economies of scale, technology, and efficiency improvements, their costs are now below those of nuclear and coal and dropping below gas. This cost reduction has resulted in 90% of new electrical generation being renewables [ref. 12]. In fact, approximately 28% of the world’s electricity is produced by renewables writ large [ref. 13], with this percentage climbing rapidly.

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. 14]. There is also research regarding solar concentrator optimization for effectiveness and cost. Thin flexible external PV films are under development which could be applied to transportation devices, buildings, etc. In the case of transportation, these films could be applied to the exterior of vehicles for partial recharge underway, extending range and enabling recharge while parked. The alternative direct DEG solar energy approach is solar thermal, which is widely used to heat water. Also, solar thermal innately provides stored energy as heat with storage longevity a function of what is heated. The frontier issues for solar thermal include concentrator optimization and material heated and storage. Small hydro is also an alternative DEG energy source, obviously depending upon availability of a local water source. Then there are geothermal, with ground heat pumps as the usual DEG manifestation, piezo-electrics as a form of wind energy, and local bioreactors utilizing yard waste, kitchen scraps, and/or sewage.

Prospective DEG energy sources going forward include advanced nuclear batteries and low energy nuclear reactions (LENR) [ref. 3]. A recent NASA approach to gamma nuclear batteries has indicated orders of magnitude greater energy density (up to some 22 kWs/kg of isotope) than existing nuclear batteries and lasts for years. The isotopes are the energy storage approach so chemical batteries and other storage options are not needed for many applications. The nuclear battery design scales from milliwatts to tens of megawatts, so they can provide distributed generation not only to an individual holding but to an individual application at that location. Radiation shielding is incorporated as part of the nuclear battery internal design. The theory of this nuclear weak force battery is straightforward, and the physics has been proven experimentally. LENR is an experimental artifact thought to involve the nuclear weak force with currently no validated theory. In three decades of experiments there was negligible radiation. The LENR demonstrated, and estimated from the extant theory, energy density is a factor of ten thousand times chemical.

Energy Conversion

Optimal utilization of DEG may require energy conversion processes, wherein energy is converted from one form to another form [ref. 3]. The most common conversions desired are heat into electricity and electricity into heat, the latter a straightforward process. The losses associated with most systems are in the form of heat, which can be regenerated into electricity. There are many extant conversion approaches that are efficacious depending upon system design instantiations. Regeneration 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 include thermal electrics (utilizing spatial temperature gradients, some 5% to 20% efficiency), piezo-electrics, utilizing mechanical movements (with an efficiency up to 80%), thermal photovoltaics utilizing radiated infrared (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 with 40% efficiency), fuel cells, which convert chemical energy to electricity at 80% efficiency, and solar cells/photovoltaics, which convert photons to electricity at an efficiency up to 50% [ref. 3]. Higher system conversion efficiencies have been and can be operationally obtained by combining several conversion processes including converting the heat produced by PV solar cells. These conversion approaches are utilized in energy regeneration as well as for primary usage. All 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 NASA researcher (Sang Choi) invention of a new approach to thermal-electric (T-E) conversion, with efficiencies predicted to be above 20% [ref.16].

Energy Storage

The usual energy storage modalities are variations of thermal, electrical, mechanical (i.e., pressure, springs, flywheels, gravity), and chemical [ref. 3]. Due to the intermittency of solar PV and terrestrial wind energy, if these generation approaches are utilized then storage is required. The other DEG renewables, such as geothermal, hydro, solar thermal, and biomass/biofuels, are either base load or self-storing and do not require separate storage. The spectrum of energy storage approaches is immense and becoming available at ever lower cost [ref. 17]. There are efforts for seasonal storage, usually via thermal storage, storing cold in the winter and heat in the summer. Electric vehicle batteries are under study as a collective storage option in the evening. Green hydrogen (H_2) generated by inexpensive renewable energy is being considered 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 DEG utilization. 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 and thermal batteries, etc. The nominal electric to electric storage efficiencies are [ref. 18] compressed air (40% to 70%), pumped hydro (70% to 85%), chemical batteries (80% to 95%), hydrogen (25% to 45%), flywheel (70% to 95%), and liquid air (up to 70%).

For heat storage, water is the standard with the frontiers being chemical structure, material thermal storage, zeolites, and liquid metals. Frontier batteries include lithium metal (~ 500 Wh/kg), lithium air (6X plus Lithium ion), solid state "glass" batteries, structural batteries (store electricity or H_2 in a structure), metal air batteries - Al, Li, Zn, and seawater batteries. Storage has reduced in cost by 70% over three years.

Energy Conservation

There are generally two ways to solve a problem: either raise the bridge, or lower the river, the latter approach reduces the severity of the problem to be solved. Energy conservation reduces the energy generation needed by DEG [ref. 3]. The major cause of the now decade long decline in energy use per person appears to be primarily energy conservation [refs. 19 – 21]. The nominal definition of energy conservation is the 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 44% by 2040, and 50% to 60% by 2050. These are obviously large percentages with major econometric and climate impacts. For DEG, 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, motion-activated lights, passive solar, natural building ventilation, smart meters, occupancy sensors, passive solar, heat pumps, shelter belts, and light-emitting diode (LED) lighting, along with regeneration from waste heat including dryer venting and ventilation air flows. Then there are the major improvements (approximately 30%) in the efficiency of electric motors, which, overall are responsible for 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 the 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 more than 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, including via 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. For 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.

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, low pressure drop membranes, and improved fluid flows/reduced pressure drop throughout. A major emerging energy utilization increase that has many concerned is the large additional air conditioning loads due to climate change ambient temperature increases. Technology is developing to utilize the atmospheric transmissibility of 8-to-13-micron IR to radiate heat to space. Tens of degrees cooling has been demonstrated and application development is underway [ref. 22].

Benefits of DEG

DEG is not subject to the many vulnerabilities or sources of failure associated with the grid including power lines down due to falling trees, storms including ice storms, auto accidents, cyber-attacks, and electro-magnetic pulses (EMP) associated with either solar storms or nuclear detonations. Experience in areas subjected to serious storms demonstrates that DEG systems have excellent reliability/resilience. DEG enables living off the wire grid, when combined with such as the developing personal electric vertical take-off and landing (eVTOL) air vehicles and other technologies, enables the capability to live anywhere, off roads, and without wires. The economies of scale for the huge numbers of DEG sites (including individual homes/holdings) creates opportunities for serious cost reductions. DEG obviates the approximate 6% combined grid transmission losses and transformer losses. DEG obviates the need for major requisite grid capital investment and maintenance costs and will probably ultimately replace the aging grid. DEG also empowers the property owner, providing total control of energy approaches including their costs and promotes energy conservation. Estimates of energy cost reductions just due to reduced operating costs for DEG compared to the central generation and distribution approach/costs are on the order of 50% [ref. 23]. DEG reduces the costs of decarbonization and promotes timely use of renewables.

DEG Enables the Rise of a Do-It-Yourself Mode of Living [ref. 3]

Before the Industrial Age, few had “jobs”, and most were farmers living almost wholly in a do-it-yourself (DIY) 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 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. 17], 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 people 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.

Frontiers of DEG Technologies

The present efficiency levels of DEG, solar PV depending upon specifics, is nominally in the range of 20%, without regeneration of heat losses. Wind efficiency is nominally on the order of 40%. Approaches to increase overall PV efficiency per unit of surface coverage include Sun tracking, utilizing more of the solar spectrum, IR PV underneath to capture ground radiation, regeneration of the heat losses, solar concentrators and designing for two electrons per photon. These are projected to increase PV efficiency by a factor of 2 plus. Wind generation efficiency can be improved by moving the device higher where the wind velocity is greater, using ducted designs, maintaining optimal alignment with the wind direction, blade flow separation control, and reduction approaches for vortex drag due to lift.

DEG in Space

Space energetic sources include fission nuclear reactors, solar PV, fuel cells, and radioisotope thermoelectric generators (RTGs) [ref. 24]. Distance from the Sun nominally precludes PV utilization much beyond Mars. Fuel cells require significant amounts of fuel, which, on the Moon, Mars, and many asteroids, can be produced as in-situ resource utilization (ISRU) from on-body water resources. Fission nuclear reactors, due to size, weight, and radiation are currently planned as central generation sites with wired distribution (an electric grid), although energy beaming to user sites could also be utilized. The nuclear RTGs used thus far are capable going forward of 10 to 20 watts per kilogram of isotope and are heavier than a nuclear reactor on an energy density basis. Therefore, they are used primarily to power sensors/instruments and controls. The usual until now distributed space energetics sources have been PV out to the vicinity of Mars, fuel cells, and RTGs, with chemical batteries as a distributed storage but not as a generation energy source. What is now on the way to rapidly changing space power and energy is the recent invention of advanced nuclear batteries, with up to orders of magnitude greater energy density and much reduced overall weight (alpha down to order one, up to 22 kWs/kg of isotope vice usual 20 Ws/kg). These last for years and open up an entirely different in-space transportation and surface mobility trade space (e.g., ref 24). The NASA version is the quantum energetic process based Nuclear Thermionic Avalanche Cell (NTAC), which releases a large number of intra-band/ inner shell electrons via utilizing high energy photons of 100 keV to MeV, a gamma nuclear battery [ref. 25]. The design scales from powering phones to tens of megawatts, with the far longer-term operability expected of nuclear vs. chemical batteries. The new nuclear battery designs could power (in a distributed manner) nearly everything in space including in-space and on body habitats, ISRU, and on-body and in-space transportation. Estimates indicate they could power Variable Specific Impulse Magnetoplasma Rocket (VASIMR), a high thrust magnetohydrodynamic drive (MHD) propulsion system with a specific impulse (I_{sp}) of 6,000 seconds. This could enable a 200-day round trip to Mars, which would greatly alleviate in-space radiation and micro-gravity health concerns. Other potential utilization includes powering satellites, terrestrial and deep space mining, shipping, manufacturing, utilizing nuclear fission waste as fuel, generating electricity, and reducing radioactivity in the process. For on-surface transportation, there are three obvious possibilities to utilize this new nuclear capability: lower speed, nuclear ramjets, and nuclear rockets. On Mars, such a nuclear battery could supply propulsive lift for long haul, as well as short haul via intaking CO_2 from the atmosphere and pressurizing it via electric motors turning axial flow compressors, which is exhausted downwards using ejector nozzles to provide lift and thrust. For higher speeds up to high supersonics, the new nuclear batteries could either power heating and additional compression for an atmospheric ramjet or heating for a conventional rocket, with or without addition of chemical energy using on-planet ISRU derived propellant or propulsive mass. There are a multitude of ISRU applications for such nuclear batteries, especially for autonomous and lunar night operations. Electrolysis of ice into hydrogen propellant and oxidizer to enable a lunar economy or for return fuel from Mars requires far more power than current technologies can deliver (except much larger and more expensive nuclear reactors). Projections of full-scale performance suggest that the new nuclear batteries can provide essentially all on-body/planet energy requirements, including those that require portability as well as, via powering tethers for propulsion, clean up space debris economically.

Concluding Remarks

There are two seriously major ongoing revolutions in power generation, storage, and distribution. The first of these is a massive shift from fossil fuels and nuclear to a range of renewable energy generation and storage with solar PV and wind (e.g., terrestrial, offshore, high altitude) the dominant approaches. The second is a two-part revolution based upon the scalability of renewable energy sources and storage to the individual holding. This is termed distributed energy generation or distributed energy resources. Part one of this concomitant second energy revolution is to utilize an ever-smarter grid and replace an increasing amount of central generation by distributed generation, managed by a much-altered grid. Part two is the probable, developing endpoint of these energy revolutions, a back-to-the-future shift to distributed generation and storage off grid, grid independence, which would greatly alter-to-atrophy the 20th century centralized generation and energy sourcing industry. The enabler for these revolutions is the historic cost reductions in both generation and storage for the renewables. Their costs have dropped below fossil fuels and nuclear, including the new miniaturized nuclear approaches, and the costs for renewable generation and storage are still plummeting. Some are starting to cite the emergence of energy too cheap to meter, which was applied long ago to nuclear and obviously never transpired. It is primarily cost reductions which spurred these revolutions, along with their obvious and huge favorable impacts upon climate, reductions in CO_2 generation. Ever cheaper renewable electricity is also rapidly now reducing CO_2 generation by manufacturing, buildings, transportation, and agriculture. In this process, there are different winners than for the 20th century centralized, generated and distributed via wires fossil fuel-based energy industries. Most countries can become energy independent, the price of energy will reduce much, individuals vice corporations will control their energy, and energy will be far more resilient to solar storms, cyber and weather.

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