Homeland Defense & Security Information Analysis Center

HDIAC

ALTERNATIVE ENERGY

An Enabler of Military Capability

STATE OF THE ART REPORT

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STATE OF THE ART REPORT:

Alternative Energy: An Enabler of Military Capability

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Table of Contents

Section 4

Section 5

Section 6

Section 7

List of Figures

List of Tables

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Chris DePuma is an electronics engineer in the Spacecraft Electronics branch of the NRL. He has supported multiple programs during his time at the lab, most notably he is the program manager for the Photovoltaic Radiofrequency Antenna Module (PRAM). This experiment, currently flying on the Air Force X-37B, is a prototype of a future Solar Power Satellite that aims to convert solar energy in space to a microwave transmission that can be sent back to earth for terrestrial use. Mr. DePuma has also spent significant time supporting the DARPA-funded, NRL-led Robotic Servicing of Geosynchronous Satellites (RSGS) program. For RSGS he has contributed to the environmental test campaign, as well as the harness design efforts.

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Executive Summary

The Homeland Defense & Security Information Analysis Center (HDIAC) regularly develops state of the art reports (SOARs) in order to provide a compendium of scientific/technical articles that summarize the most current state of research in topic areas of importance to the Department of Defense (DoD). These SOARs are a means of satisfying user needs for authoritative information directly applicable to their ongoing work.

Alternative Energy is one of the HDIAC's eight technical focus areas and was chosen as the subject of this report due to its importance to the DoD. Alternative Energy is composed of novel, non-traditional, and emerging sources and technologies for harvesting, generating, storing, transmitting/transporting, and reusing energy to sustain growing energy needs, including that of the DoD.

The *National Security Strategy of the United States* recognizes that U.S. energy dominance will ensure that markets are free and U.S. infrastructure is resilient and secure while simultaneously guaranteeing diversified access to energy and good environmental stewardship. Additionally, the *National Security Strategy* offers five priority actions under the step "Embrace Energy Dominance," three of which (Ensure Energy Security, Attain Universal Energy Access, and Further America's Technological Edge) demand the development of alternative energy resources.

By design, the *National Defense Strategy* supports the *National Security Strategy*; it outlines an operational environment where "every domain is contested – air, land, sea, space, and cyberspace," and emphasizes that the "homeland is no longer a sanctuary." Preparing for the battlefield of 2025 and sustaining resilient installations necessitates the assured delivery of cyber-secure fuel and power in contested environments against near-peer competitors. In today's technology-dependent environment, energy requirements are inseparable from DoD's mission requirements.

Energy is an essential enabler of military capability, and the DoD depends on energy-resilient forces and facilities to achieve its mission. In FY 2018, the Department consumed over 85 million barrels of fuel to power ships, aircraft, combat vehicles, and contingency bases at a cost of nearly $9.2 billion. Further, recent research shows that the U.S. military consumes more liquid fuels and emits more CO2e (carbon-dioxide equivalent) than most countries. At over 500 worldwide military installations, the DoD spent $3.4 billion in FY 2018 on energy to power over 585,000 facilities and 160,000 non-tactical vehicles. In FY20, the DoD requested more than $3.6 billion for the execution of operational energy initiatives. These investments procure new or upgrade existing equipment, improve propulsion, adapt plans, concepts, and wargames to account for increasing risks to logistics and sustainment, and enhance the role of energy considerations in developing new capabilities.

In addition to its critical role in installation support and management, energy is a decisive enabler on the modern battlefield. Over the last two decades of near continuous combat, the U.S. military has become a more lethal and networked force; however, this has come at a price of increased fuel consumption. This has, in turn, increased the logistics footprint and weight of the force, hindering mobility and responsiveness as well as driving up costs. Further, resupply of fuel to forward operating bases in austere locations puts lives at risk and commits precious combat forces to security missions – it places Soldiers, Sailors, Airmen, and Marines squarely in harm's way as forward deployed forces seek to keep fuel flowing to key warfighting enablers such as generators, aircraft, tanks, and trucks. Tactically viable alternative energy solutions including solar, wind, hybrid, kinetic recovery, nuclear, and biofuels for use at remote, austere locations can ultimately reduce the combat load and create a more agile and lethal force at lower cost and risk. This will support the needs of dispersed and highly mobile forces by enhancing the operational versatility of assets traditionally dependent on fossil fuels.

This SOAR reviews the current state of a selection of novel, non-traditional, and/or emerging sources and technologies for harvesting, generating, and reusing energy. It offers synopses of new programs; summaries of significant technological breakthroughs and technology applications; highlights of outstanding developments; and impacts to the DoD.

1

Introduction

The use of alternative energy sources plays a major role in the national security of the United States. These forms of energy are developed using domestic resources, and they have little if any reliance on foreign sources of energy, nor are they impacted by fluctuations in foreign energy markets. Further, their use allows the United States to set a global example for other large economies, demonstrating the benefits of alternative energy use in reducing greenhouse gas emissions from the burning of fossil fuels.

1.1 Definitions of Alternative Energy, Renewable Energy, and Sustainable Energy

Although the terms alternative energy, renewable energy, and sustainable energy are often used interchangeably when discussing energy, each has an important distinction and role in powering the world.

- Alternative Energy is composed of novel, non-traditional, and emerging sources and technologies for harvesting, generating, storing, transmitting/transporting, and reusing energy to sustain growing energy needs, including that of the Department of Defense (DoD). It refers specifically to energy sources that are not powered by fossil fuels such as coal, natural gas, and oil.
- Renewable energy is a type of alternative energy that is not depleted when it is used. Specific examples of renewable energy are wind, solar, and hydroelectric. Nuclear fission would not be considered a renewable energy source since it results in a depletion of the fuel (i.e. atoms of the uranium-235 isotope) used in energy production.
- Sustainable energy refers to the practice of meeting present energy needs without compromising or impacting the ability of future generations to meet their energy needs. Thus, the term is not a category of energy types in itself.

1.2 DoD Energy Needs

In its *2016 Operational Energy Strategy*, the DoD recognizes that:

> *"[e]nergy is the fundamental enabler of military capability, and the ability of the United States to project and sustain power necessary for defense depends on the assured delivery of this energy. It must be available at home and abroad, over great distances, through adverse weather, and across, air, land, and sea, often against determined adversaries [1]."*

Further, DoD's most recent Annual Energy Management and Resilience Report (AEMRR) points out that "energy requirements are inseparable from the Department's mission requirements, whether discussing weapons platforms or the installations and systems that support those capabilities around the globe. [2]"

The DoD's Operational Energy Strategy discusses the term "installation energy" and defines it as the "energy used to power installations and enduring locations… [1]" In FY18, the DoD's installation energy requirements account for 30% of all the Department's energy use [2]. The DoD recognizes the need to reduce its significant demand for installation energy, especially fossil fuel use, with five specific objectives [3]:

- Reduce the demand for installation energy and water through conservation and efficiency
- Expand the support distributed (on-site) energy for mission assurance
- Improve the energy grid and storage resilience of our installations
- Leverage advanced technology for energy resource efficiencies and increased security
- Improve the cybersecurity of mission critical facility related control systems

1.3 Current State of Alternative Energy Use

One recent estimate of greenhouse gas emissions points out that from the start of operations post 9/11 through 2017, the DoD accounted for more than 1.2 billion metric tons of emissions from the use of fossil fuels [4]. Expanding the use of alternative energy resources has a role in DoD's ability to reduce its greenhouse gas emissions and achieve its installation energy objectives. In its most recent AEMRR, the DoD achieved a 15.76 percent renewable energy use (with its required goal set at 15 percent) [2].

1.4 Reducing DoD Reliance on Commercial Grid by Transitioning to Alternative Energy Sources

The DoD is heavily dependent on the U.S. commercial power grid to heat, cool, and power hundreds of thousands of buildings and structures at more than 500 military installations world-wide [3]; however, this power is not always delivered reliably. In FY18, DoD installations experienced more than 500 energy utility outages lasting eight hours or more [2]. By transitioning to alternative energy sources, the DoD can reduce its reliance on commercial utilities for power, and also reduce its greenhouse gas emissions. By 2025, the DoD's goal for installation energy provided by alternative and renewable sources is 25 percent [2].

1.5 Alternative Energy to Reduce the Warfighter's Logistics Footprint

The DoD's dependence on fossil fuels is not limited to its traditional bases and installations. Over the last two decades of near-continuous combat, the U.S. military has become a more lethal and networked force; however, this has come at a price of increased fuel and battery consumption. This has, in turn, increased the logistics footprint and weight of the force, hindering mobility and responsiveness and driving up costs.

Resupply of fuel to forward operating bases in austere locations also costs lives; in a 2009 study undertaken by the Army Environmental Policy Institute, casualty factors to soldiers and civilians transporting fuel to consuming units were calculated to be 0.042 for Afghanistan and 0.026 in Iraq – that is 0.042 casualties for every fuel convoy in Afghanistan or one casualty in every 24 fuel resupply missions. This same study estimated that, in 2007, the annual number of fuel convoys per year was 5,133 in Iraq and 897 in Afghanistan [5]. Hence, if better ways to generate power can be found, there will be a commensurate reduction in risk to Soldiers, Sailors, Airmen, and Marines. Tactically viable alternative energy solutions including solar, wind, hybrid, kinetic recovery, nuclear, and biofuels for use at remote, austere locations can ultimately reduce the combat load creating a more agile and lethal force at lower cost and risk.

This SOAR reviews the current state of a selection of novel, non-traditional, and/or emerging sources and technologies for harvesting, generating, and reusing energy. It offers synopses of new programs; summaries of significant technological breakthroughs and technology applications; highlights of outstanding developments; and impacts to the DoD.

2

Solar Energy

2.1 Introduction to Solar Energy Technology

As the DoD's operational environment changes, transitioning to new sources of energy is critical to maintaining military capabilities. Harnessing the power of the sun offers a multitude of ways to provide energy to the DoD. The diverse applications and low cost of solar power make it an attractive form of alternative energy for the DoD to meet its energy needs. Creating and sustaining resilient installations is a key priority of the National Defense Strategy [6], and security and resiliency are key components to helping ensure that the DoD has a sustainable energy platform.

For many years, the Department has looked to solar energy to do just that. The military has used portable solar arrays to power operations in remote areas. Solar energy provides an innovative and renewable source of power. Alternative energy sources not reliant on fossil fuels have been shown to eliminate the need for risky re-fueling missions that can often be seen as potential targets for enemy attacks [7].

Further, large, fixed military bases provide prime locations for solar panel fields. The majority of the DoD's energy consumption occurs on the hundreds of fixed installations and facilities it operates across the globe [8]. Large solar arrays sited on military installations can provide the DoD with a reliable and resilient energy source that also insulate the installations from vulnerabilities such as commercial grid outages. For example, today a five-megawatt (MW) solar system at Fort Campbell, KY provides ten percent of the base's energy needs [9]. Shaw Air Force Base in Sumter, SC installed over 5,000 solar panels in family housing, cutting electricity use by more than 40 percent [9].

2.2 Current Solar Technologies

Solar energy technologies are classified into two main categories, photovoltaic (PV) and concentrating solar power (CSP).

2.2.1 Photovoltaic

Frequently used for residential purposes in the form of panels, PV creates a flow of electricity by absorbing photons from sunlight and converting it to electricity. Figure 2-1 shows the process of photovoltaic generation of electricity. The photovoltaic effect was first used in 1954 when a silicon solar cell generated electricity following exposure to sunlight [10]. Deployment of photovoltaics on a large scale has widely contributed to powering homes, businesses, and communities around the globe.

Solar cells are typically comprised of semi-conductor materials such as thin-film, monocrystalline, or polycrystalline [11]. Silicon makes up 90% of solar cell modules and the crystalline silicon cell's lattice structure creates more efficiency in the process of transforming light into energy. Thin-film solar cells are typically composed of cadmium telluride or copper indium gallium diselenide. As solar cell technology moves away from bulky solar panels that many are familiar with, thin-film technology will make these lighter weight solar cells useful for many new and innovative applications; for example, placement in windows that can then generate electricity or placement in a soldier's backpack or other equipment to generate needed electricity for their gear [10]. Further research is being conducted into new PV technology to further improve the efficiency of solar cells using new materials, such as perovskites, and is discussed later in this section.

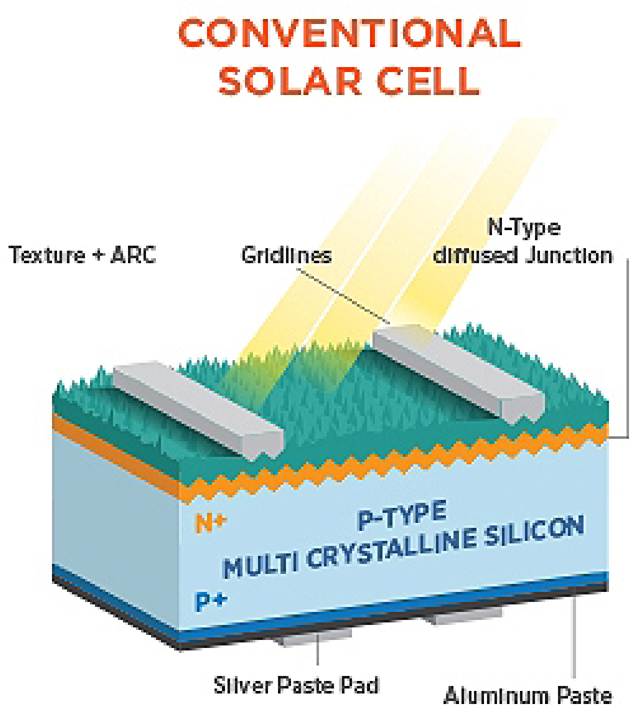

Figure 2-1. Conventional Solar Cell [12].

As the largest energy consumer in the United States, the DoD already makes significant use of PV systems to harness the power of the sun. For over a decade, the Marine Corps has used solar energy powered by a building-integrated PV system for vehicle charging and refueling stations. In addition, the Marine Corps Air Station Yuma in Arizona has installed 102 kilowatts (kW) of PV on existing structures [13]. In October of 2019, the USAF completed a 42-acre solar facility in New Mexico at Holloman Air Force Base. The facility is comprised of 56,000 thin-film modules [8].

2.2.2 Concentrating Solar Power

Concentrating solar power technology uses mirrors to reflect and concentrate sunlight to a single point. The sunlight is converted to heat at the point of concentration with the resulting thermal energy being used to produce electricity. This type of power is typically used for large-scale industrial purposes, such as powering generators, engines, or other large mechanical devices. CSP systems can be thermal storage, power tower, linear concentrator, or dish/engine systems [14]. The benefits of CSP systems include significant power on demand and reduced energy costs gained from technological improvements (see Figure 2-2).

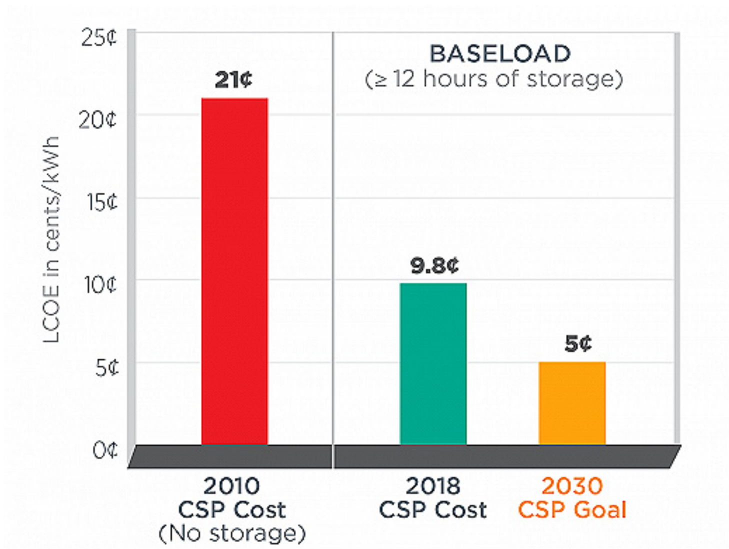

Figure 2-2. CSP Cost [10].

2.3 Emerging Technologies

Reliable generation of clean energy is constantly being addressed through the development of new technologies; as such, several new advances have emerged in the solar industry. Although the aesthetic of solar panels may have previously turned some away from considering them on the roofs of homes and other buildings, a new “solar skin” can camouflage the technology into the roof material without interfering or limiting the solar energy conversion process [16]. According to the researchers at the Massachusetts Institute of Technology (MIT), SolarSkin employs selective light filtration to display an image, such as a sign, or mimic roof shingles, and only requires a miniscule amount of light to reflect an image while maintaining high efficiency [17].

Higher efficiency in solar cells has also long been sought by the industry and has been the focus of significant research. Improvements in solar cell technologies have lowered the cost per watt and made solar energy more accessible, affordable, and reasonable to individuals. One solar cell technology, the Perovskite solar cell, has had rapid increases in conversion efficiency over prior iterations of the technology [18]. Perovskite cells are thin-film devices actively being studied in the solar energy industry. Before wide commercialization can occur however, researchers have to address shortcomings such as the lack of durability with prolonged exposure to heat and light. That said, Perovskite cells have the ability to convert ultraviolet light and visible light into electricity extremely efficiently. If paired in tandem with crystalline silicon they could be prime absorbers and deliver more power [18]. A thin film Perovskite solar cell and the tandem solar cell are shown in Figure 2-3.

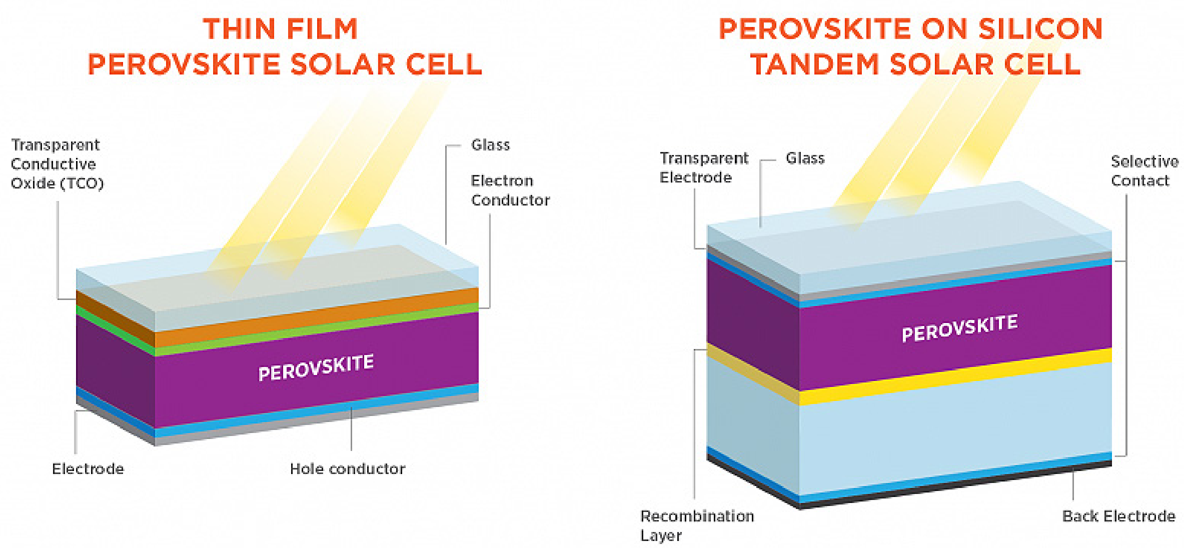

Figure 2-3. Perovskite Solar Cell [18].

Another solar cell technology that yields gains in efficiency, and therefore reduces the unit operating cost, is the solar thermophotovoltaic device (STPV). Researchers at MIT have developed the STPV, a modified PV, to address the energy wasted by solar panels. Typically, during the conversion process from sunlight to energy, traditional solar panels are not able to harness the full energy generated from the process. By adding a new layer to the solar panels, researchers are "converting broadband sunlight to narrow-band thermal radiation tuned for a photovoltaic cell [19]." They have further demonstrated the increase in efficiency by comparing a normal PV cell with the enhanced version through a process of suppressing unconvertable photons. The project utilized pairing of a one-dimensional photonic crystal selective emitter with a tandem plasma–interference optical filter [19]. After measuring the solar to electric conversion rate, the researchers at MIT found a higher efficiency with the modified STPV:

> *"We measured a solar-to-electrical conversion rate of 6.8%, exceeding the performance of the photovoltaic cell alone. The device operates more efficiently while reducing the heat generation rates in the photovoltaic cell by a factor of two at matching output power densities. We determined the theoretical limits, and discuss the implications of surpassing the Shockley–Queisser limit. Improving the performance of an unaltered photovoltaic cell provides an important framework for the design of high-efficiency solar energy converters [20]."*

Peak efficiency is perhaps the most sought-after development in the solar cell industry. Efficient solar cells simply are more cost-effective and have driven innovation since the late 1970s. Figure 2-4 shows the development of highest confirmed conversion efficiencies for research cells for a range of photovoltaic technologies, plotted from 1976 to the present. The cell efficiency results are presented in semi-conductor categories: multijunction cells, single-junction gallium arsenide cells, crystalline silicon cells, thin-film technologies, and emerging photovoltaics. The National Renewable Energy Laboratory (NREL) utilized a standardized form of testing:

"defined by the global reference spectrum for flat-plate devices and the direct reference spectrum for concentrator devices as listed in standards IEC 60904-3 edition 2 or ASTM G173. The reference temperature is 25°C, and the area is the cell total area or the area defined by an aperture [21]."

Based on these findings, multi-junction cells with four or more junctions are the most efficient subcategory. Multi-junction solar cells utilize different layers when absorbing different wavelengths of light providing a higher conversion rate of sunlight into electricity than a single junction cell. As previously discussed, Perovskite cells take a tandem approach to the multi-junction cell providing higher efficiency.

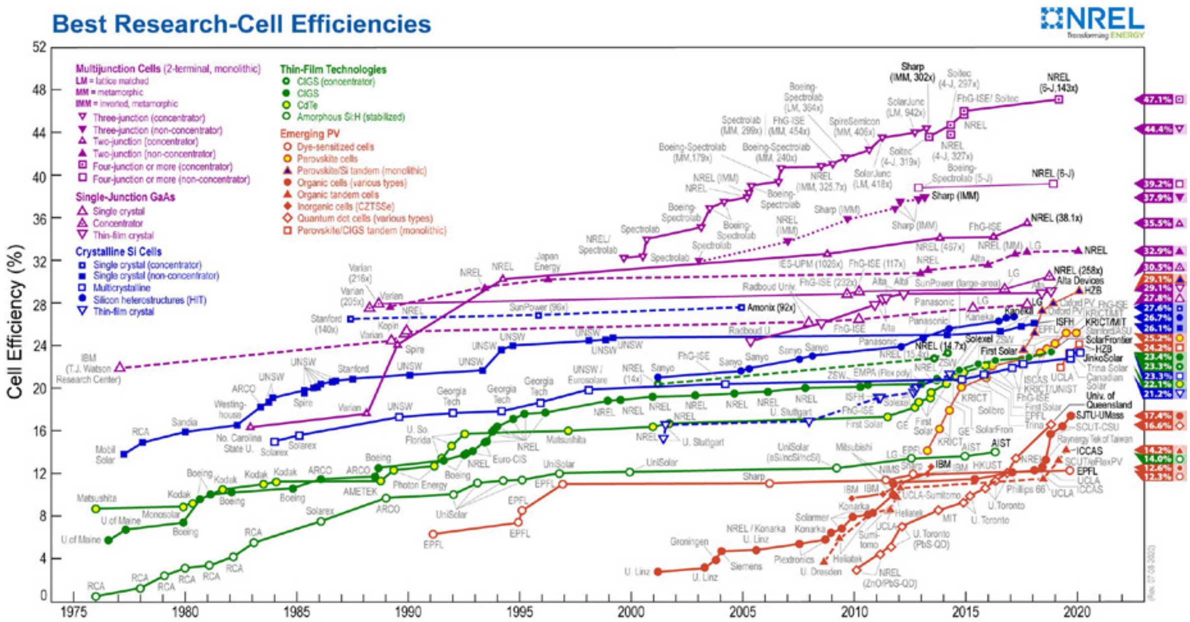

Figure 2-4. This research cell efficiency tracking plot is courtesy of the National Renewable Energy Laboratory, Golden, CO [21].

Another solar technology under development is the solar thermal fuel (STF). The STF is a solid-state device that uses a chemical to capture solar radiation, stores it for a period of time, and then releases the stored energy when needed [22]. Instead of simply storing the heat via absorption in a material (which can dissipate over time even with the best insulation), the STF mimics a battery in that it captures the energy at the molecular level of the chemical material. This type of chemical storage system decreases the amount of heat dissipated over time by keeping the energy in a stable molecular formation [22].

2.4 State of the Art

A significant innovation that is now being actively researched is the idea of a solar roadway. A solar roadway is "a road that has some sort of solar panel technology attached to it [23]" and takes advantage of existing road infrastructure by attaching solar panels to directly to the road surface for the purpose of producing electricity for the electric grid. A study by NREL suggests that the approximately 18,000 square miles of land covered by roads in the lower 48 states could generate 80% of the nation's energy needs if covered with roadway solar panels [23]. (In 2018, the Bureau of Transportation Statistics reported that there are more than four million miles of public roads in the United States [24]). Although putting solar panels on roads raises concerns about durability and cost-effectiveness, these concerns can be addressed by newer solar panel technologies. In older technology, solar panels are typically covered with a film of fragile glass. Solar Roadway's Route 66 experiment used more durable tempered glass in their solar cell and LED lighting system, aiming to withstand the weight of a semi-trailer truck with the added benefits of lighting the roadway and heating the road to remove precipitation [25]. Although, as of this writing, the project has stalled due to a variety of factors, it provides insight into a potential use of solar-power technology in a method not previously considered, and it highlights how roadways and other existing infrastructure can be used for innovative applications.

Solar-powered wearable devices have been around for quite some time, however the ability to incorporate solar cell technology into clothing textiles has recently emerged. Developed prototypes have required an extremely thin PV layer, and electrically conductive polyester makes up the electrodes while the solar cells are laminated to retain strength [26]. Developers believe that fabric-based solar cells could be ready for market launch in approximately five years. This technology would provide a new method of portable power with capability to charge small electronic devices, such as a phone or radio, from clothing. Such a means of power generation offers obvious advantages for military power generation in austere environments.

2.5 Impact on DoD Energy Needs

Research and development in solar power technology is a key component that can aid the DoD's desire to ensure a secure, reliable, and affordable energy supply to support both the operating forces as well as installations. Advances such as highly efficient multi-junction and tandem solar cells, wearable solar technology, and developments such as solar roadways can reduce lifecycle operating costs and manage future commodity price volatility, while simultaneously reducing greenhouse gas emissions and dependence on foreign fossil fuels. As commercial solar energy continues to increase in capacity, the DoD is planning to increase its use of solar energy. This use of solar energy and other alternative and renewable energy sources, including those discussed in follow-on sections in this report, will lead to a continuing improvement to its energy security and resiliency.

3

Harnessing Solar Power via Satellites

3.1 Introduction

Credited with predicting the large-scale negative contribution of fossil fuel combustion to atmospheric carbon concentration in 1896, Svante Arrhenius and his collaborators shared a long realized need for alternatives to fossil fuels for global energy production [27]. The significance of Arrhenius' statement was not fundamentally understood by scientists until half a century later in the 1950s, when the increasing concern for the environmental impact of burning fossil fuels finally spread throughout both the scientific community and general public. This generated the first proposal to harness the most abundant energy source in our solar system, sunlight, locally in space by Peter Glaser in 1968 [28].

Figure 3-1. One possible implementation of a solar power satellite [29].

The concept of space solar outlined by Glaser involved two components that aligned with the then-existing two-fold structure of earth-space systems: 1) a space segment involving a large spacecraft utilizing photovoltaics for solar energy collection coupled with a transmission device, and 2) a ground segment to receive and convert incoming energy into a more readily storable and accessible form compatible with current energy systems. A depiction of one possible implementation appears in Figure 3-1 [29]. Since its introduction by Glaser, many significant efforts to create and develop the technology that will allow for space solar energy harvesting and transmission have been made.

3.2 Technological Elements

The functional components for solar power satellites have been separated into two primary forms for power beaming: optical and microwave; and two primary forms for collection: photovoltaics and solar thermal. Each transmission and collection scheme has its advantages and disadvantages.

Radio frequency (RF) microwave power beaming involves the transmission of electricity through conversion of sunlight to a longer electromagnetic wavelength, usually within the microwave range. This longer wavelength allows for transmission that is less susceptible to atmospheric attenuation, but requires a larger transmitting and receiving apertures [29]. Laser power beaming involves the transmission of electricity through conversion to monochromatic electromagnetic waves within the near-visible wavelength range. These shorter wavelengths of laser transmission allow for tighter beams over long distances that can be steered to specific receivers [30], and utilization of smaller transmission and receiver apertures relative to microwave transmission. Although this leads to smaller apertures, it also is subject to greater weather and atmospheric attenuation compared to microwave power beaming.

Solar collection involving photovoltaics (PVs) consists of direct conversion of sunlight into electricity via the photovoltaic effect, in which electric current is generated within a solar cell when it is exposed to light. This method of collection has long been used for space applications as a result of its relative reliability and simplicity in implementation [31]. Space solar thermal collection in principle would utilize concentrated sunlight to generate heat to allow for driving an electric generator via a heat transfer fluid. This method has a theoretical ability to operate at a high efficiency [32].

3.3 Current Approaches

3.3.1 Performance Metrics

Many solar power satellite designs encompassing these collection and transmission schemes (predominantly photovoltaics for energy collection and microwave for transmission) have been proposed. These approaches to space solar would consist of a large set of system and design considerations. Thus, allowance must be made for individual limitations and strengths of these designs. As a result, there are several performance metrics to consider for each architecture: collection/transmission area-specific mass, mass-specific transmitted power, combined energy efficiency, temperature performance range and survivability, and serviceability of the proposed design. Research and development to improve these metrics is imperative, and will have benefits for essentially all space systems.

Collection/transmission area-specific mass is a metric of interest as most solar power satellite designs must accommodate large surfaces for solar collection and transmission. In the instance of microwave transmission, large transmission antenna apertures must be considered as the transmitter portion alone has ranged from 4 kg/m^2 to 40 kg/m^2 in many proposed solar power satellites [33]. Mass specific power represents the mass required to output a given power level. This is most significant for economic modeling of space solar satellite designs and has been measured to be 4.5 W/kg in an environmentally tested element under simulated illumination of one sun (approximately 1368 W/m^2) and 5.8 W/kg under simulated illumination of two suns (which simulates operation under solar concentration). The combined energy efficiency measures the ratio between the absorbed solar light and output power. A higher efficiency reduces the amount of heat generated during sunlight conversion. The highest reported sunlight-to-microwave conversion efficiency for a sandwich module in vacuum is 8 percent, recorded at the Naval Research Laboratory (NRL) in 2012 [34]. Temperature range and space environment survivability are being explored through a recently launched space experiment [35] and work around the world points to paths to significant increases in efficiency [36] [37].

3.3.2 Proposed Architectures

Two primary space solar power satellite architectures are perpendicular to orbital plane architectures and sandwich module architectures.

3.3.3 Perpendicular to Orbital Plane

The perpendicular to orbital plane architecture is a geosynchronous (GEO) satellite with separate collection and transmission surfaces. The solar collection surface rotates on an axis perpendicular to the sun and collects energy, which is redirected to a transmission antenna pointed at earth. This antenna would be capable of transmitting large amounts of energy to rectifying antennas at receiving stations on Earth [38]. These surfaces are pointed independently of one another and are connected via a slip ring mechanism that allows for the transfer of current between these rotating structures.

3.3.4 Sandwich Module

Sandwich module architectures employ a modular approach to space solar. The sandwich module separates functions into three layers: solar energy collection, microwave conversion, and transmission of the microwave energy. These individual sandwich modules form part of a large phased array antenna. Many prototypes have been developed [39]–[41], and recent work is illuminating performance in the space environment [35]. There are plans to include additional sub-functions involved in the generation of a microwave signal and the transmission of the energy (DC power conversion, RF amplification, phase shifting, and output filtering). Figure 3-2 depicts the various layers of a sandwich module.

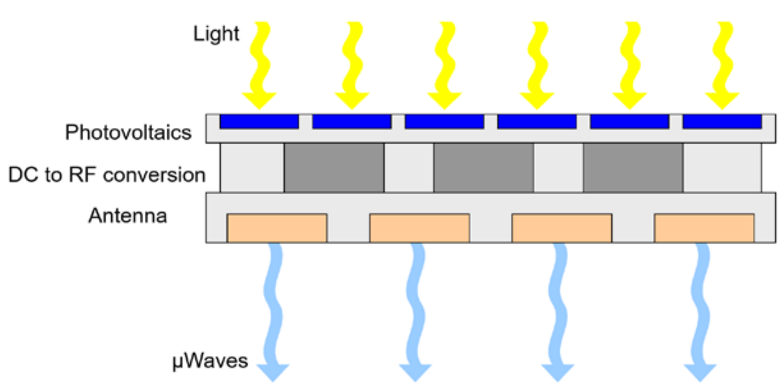

Figure 3-2. Depiction of sandwich module layers and their functions [34].

Researchers have also produced novel prototypes that enhance heat dissipation to increase the efficiency of solar energy to microwave conversion. These include alternatives to the "tile" design of traditional sandwich modules, like the "step" module design, in which additional area is provided for the dissipation of heat [34] [43]. The recent launch of the photovoltaic radio-frequency antenna module flight experiment (PRAM FX) by the NRL is the first effort to characterize the solar to microwave conversion process in space [35]. PRAM FX uses photovoltaics to collect solar energy and solid state electronics to create a 2.45 GHz microwave transmission. This flight experiment will provide vital ongoing thermal performance data that will inform future space solar satellite designs. Predecessor prototypes to PRAM FX developed by NRL can be seen in Figure 3-3. The traditional "tile" approach is on the left and the "step" approach is on the right. A 12-inch ruler is provided for scale.

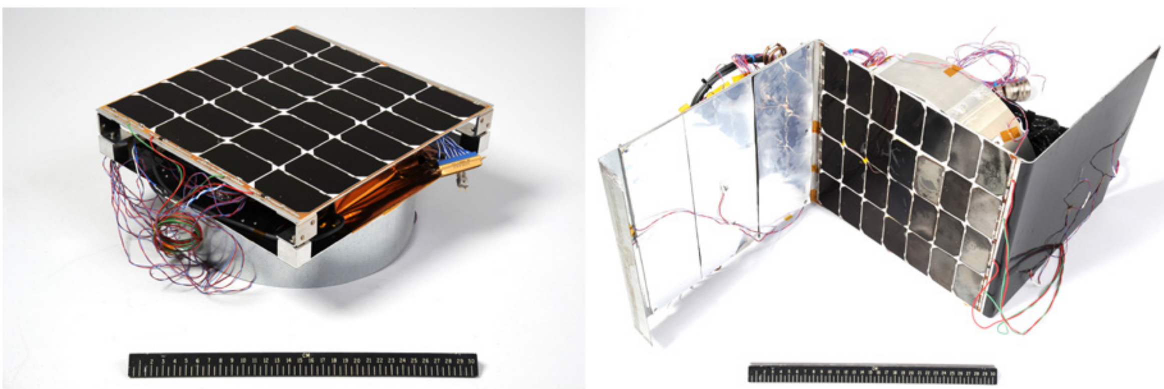

Figure 3-3. Space solar conversion sandwich modules developed by NRL [42].

Two example sandwich module architectures are the Solar Power Satellite by Arbitrarily Large Phased Array (SPS-ALPHA) and Modular Symmetrical Concentrator (MSC). These structures utilize similar modular elements for both optical and microwave transmittance apertures, removing the need for a large conducting rotating joint of historical designs [44]. Another advantage of the modular approach is an economic one, with mass production of modular components likely reducing costs. Utilizing increased solar concentration could further diminish required system launch mass and cost.

3.4 Outlook

Although significant advances have been made in the underlying technologies surrounding solar energy collection, power beaming, and developing architectures for implementation, the field of space solar is largely constrained by economic interests. These are dependent on the cost of implementation of technology, cost of access to space, and efficiency of solar energy captured in space. However, many improvements that address each respective area are being made.

NASA and DoD are actively investing in and taking advantage of recent developments driving down launch costs and expanding access to space [45] [46]. The emergence of companies such as SpaceX and Blue Origin, which aim to make space more accessible, has contributed to great progress towards reducing cost through reusability of rockets. SpaceX President Gwynne Shotwell reports a reduction in cost to "substantially less than half" from the ability to reuse boosters [47]. Similarly, Blue Origin's third New Shepard vehicle had logged six suborbital flights at the end of 2019 [48], illuminating the future of commercial reusable rocketry. Both achievements positively aid in reducing costs of access to space and implementation of space systems for tourism, industrialization, and extraterrestrial resource utilization.

Technology cost reductions have also been realized with the forays of many Silicon Valley space startups and their pioneering ideas regarding the “new space” age. Startups have generated spacecraft with capabilities and in quantities of previously unprecedented scale. By employing mass production techniques, Planet Labs, a notable emerging player in the new space industry, was able to establish a fleet of launched satellites exceeding 200 in February 2017 [49]. Other emerging organizations have followed suit with the employment of mass production, driving the cost per unit mass of spaceflight hardware to low levels, within the range of $5000 per kilogram [50] [51]. Combined with reductions in cost offered by new architectural approaches, these accomplishments drop the prospective price of electricity for solar power satellites further.

The efficiency of solar energy capture has been improved by notable advances in solid-state electronics, development of lightweight materials, and clever power conversion strategies [37]. These have enabled current technologies to achieve record-setting specific power. Research by the NRL, the California Institute of Technology, and Northrop Grumman for sunlight-to- microwave conversion modules have paved the path to increased amounts of power delivery to the ground per unit mass. Novel developments in optical power beaming technology utilizing fiber laser techniques and safety systems have also revived lasers’ potential viability as a method of power transmission for space solar [52] [53].

The world faces an abundance of immediate and long-term perils in the form of increasing population, energy demand, and the ever-growing environmental effects of climate change attributed to current energy sources. The culmination of the vision and efforts to create a solar power satellite capability promises a potential solution for a globally transmissible, clean, constant, and unlimited energy source.

4

Geothermal Energy

4.1 Introduction to Geothermal Energy

Geothermal heat radiating from the Earth's mantle contains enough energy potential to power the global electric grid more than twice over, according to the total amount of global primary energy consumption in 2015 [54]. Geothermal resources developed naturally during the planet's formation an estimated 4.5 billion years ago. Their heat flows continuously from the Earth's center to the surface - at the center of the planet, this heat reaches temperatures comparable to the surface of the sun (nearly 6,000°C). The energy potential for geothermal is so vast that it amounts to fifty-thousand times the energy of all oil and gas resources in the world [55]. Although geothermal energy would be depleted over time, it is considered to be renewable since it exists in such high abundance that the supply is considered virtually limitless [56]. It is particularly advantageous as an alternative energy source because of its benefit to grid stability, efficient heating and cooling, continuing availability at low or no cost, and little or no addition to atmospheric greenhouse gases and other emissions (Figure 4-1).

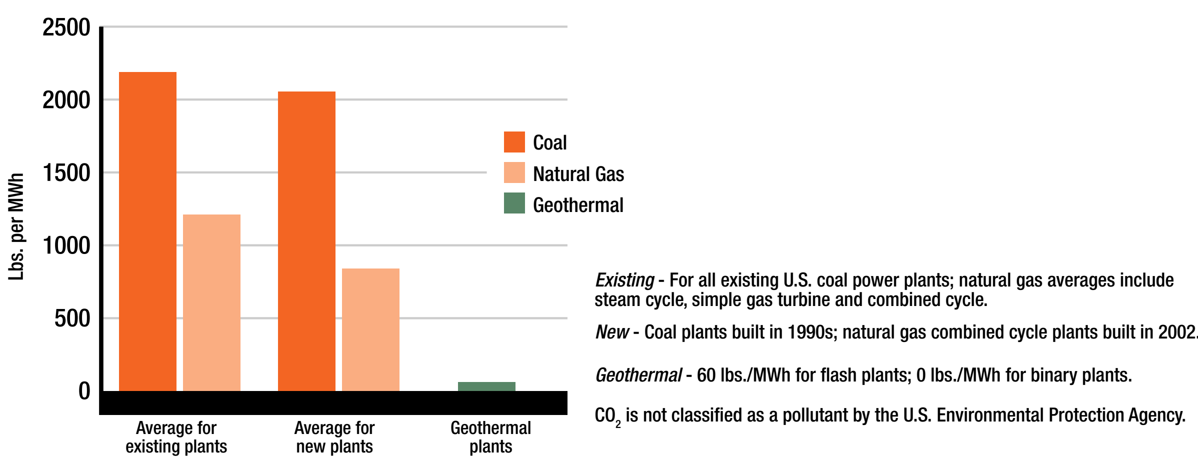

Figure 4-1. Comparative carbon dioxide emissions for U.S. Power Plants [55].

Additionally, as geothermal energy provides a continuous flow of heat, it carries advantages over solar and wind energy due to its ability to be used for a base-load power supply; load-based power supplies provide a continuous supply of electricity throughout the year and only need to be turned off during periodic maintenance, upgrading, overhaul, or service. The high (>90%) capacity factor means that geothermal power plants are able to operate all hours of the day, with steady output nearly all of the time, as opposed to wind or solar energy which are dependent on factors such as time of day and weather conditions. Because of the high capacity factor, geothermal power plants can generate about two to four times as much electricity as a wind or solar energy plant of the same installed capacity (Figure 4-2) [56].

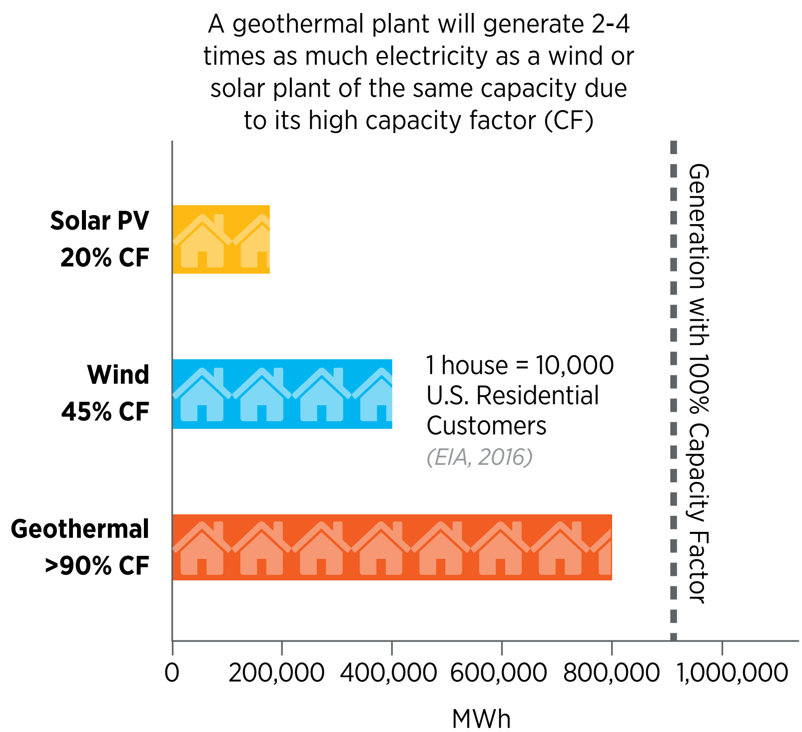

Figure 4-2. Capacity factors for geothermal, wind, and solar photovoltaic indicating annual generation (MWhe) from equivalent 100-MWe nameplate-capacity power plants [56].

Development of geothermal technologies may provide ready access to a secure, safe, domestic source of energy, consequently reducing reliance on to imports, and both U.S. communities and individuals could benefit from the use of domestic geothermal energy resources.

Though advantageous in many respects, geothermal still must overcome significant technical and non-technical barriers, including financing and costs, industry size and technology maturity, development timelines, and induced seismicity [57]. As of this writing, geothermal processes have reached a barrier for exploitation because conventional capture geothermal technologies have been constrained to existing means as newer, enhanced technologies can be both risky and costly [56] [57].

4.2 Current Geothermal Technologies

Geothermal electric power production on a commercial scale began in the United States as early as September 1960, at The Geysers geothermal field in California. To date, The Geysers is still the globe's largest geothermal field with respect to installed generation capacity, the physical dimensions of the wellfield, and the number of operational plants and wells [58] [59]. As of 2017, the United States was the global leader in both geothermal power generation and installed capacity [56].

4.2.1 Plant Technologies

Currently, three geothermal power plant technologies are used to convert hydrothermal fluids to electricity – flash steam, binary-cycle, and dry-steam [60]. Technologies such as the "flash-steam" method and the binary-cycle methods are used to harness the reservoir's heat energy, where the method of extraction depends on the type of geothermal resource (Figure 4-3). These technologies feature conventional steam turbine and generator equipment, in which the expanding steam powers a turbine/generator to produce electricity.

Flash-steam power plants utilize reservoirs with temperatures above 182°C. This high temperature water flows up through wells as a result of its own pressure; the fluid pressure decreases as it nears the surface and some of the hot water boils or "flashes" into steam. Then, the steam is separated from the liquid water, and used to power a turbine/generator unit. The leftover water and condensed steam are injected through a well back into the reservoir.

Binary-cycle power plants utilize reservoirs with temperatures of about 107°C to 182°C. The water's heat is used to bring a working fluid (usually an organic compound) with a lower boiling point, to a boil. The working fluid is vaporized in a heat exchanger and the vapor turns a turbine. The water is then injected back into the ground to be reheated. The water and the working fluid flow through separate, closed streams during the vaporization process, so there are little to no air emissions [55].

Dry-steam power plants draw from underground reservoirs of steam. The fluid to be extracted from a geothermal resource may be vapor-dominated ("dry" steam), liquid-dominated (hot water), or a mixture of the two. The Geysers in northern California, the world's largest single source of geothermal power, uses dry steam. The steam is piped directly from wells to the power plant, where it enters a turbine. The steam turns the turbine, which turns a generator. The steam is then condensed and injected back into the reservoir via another well.

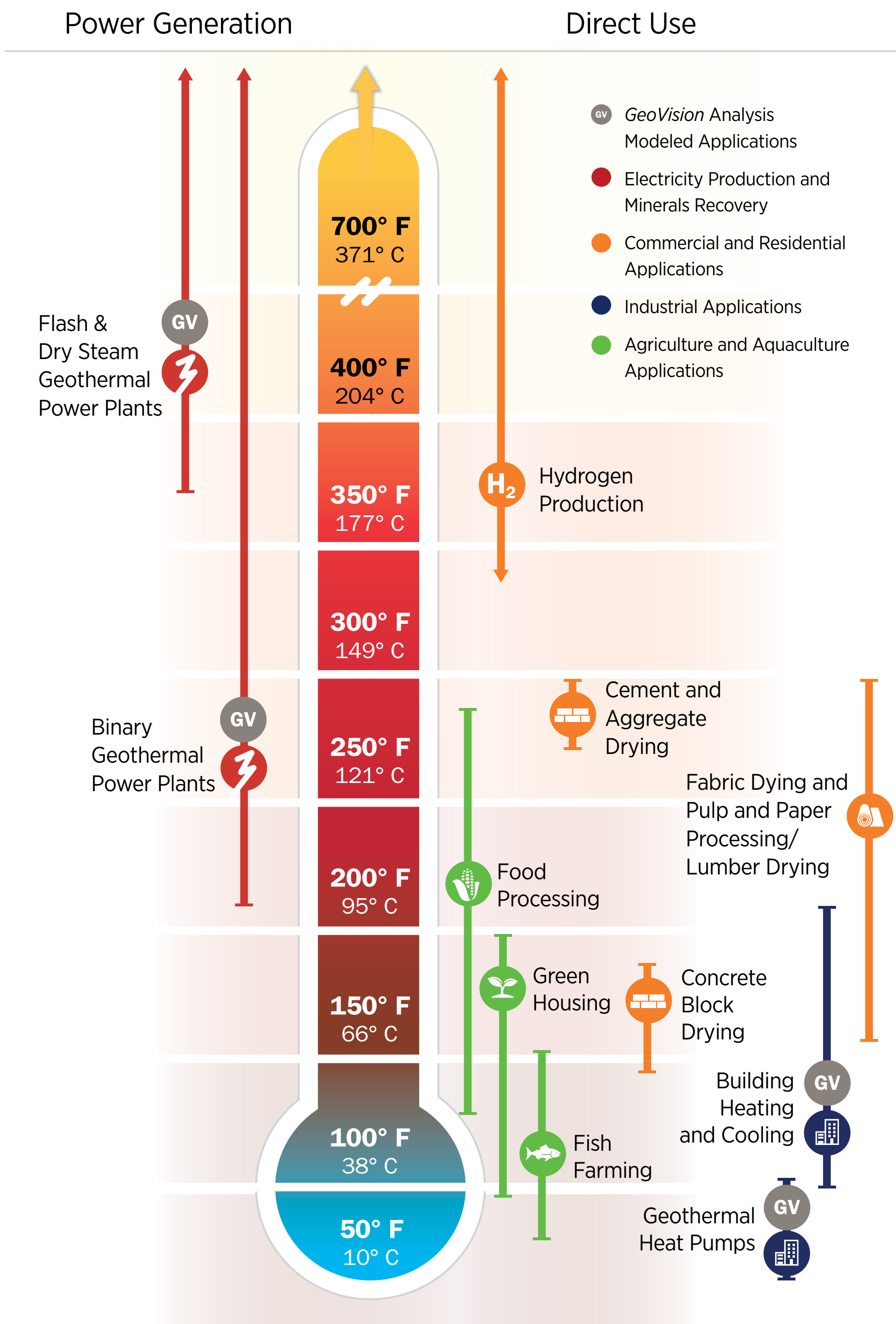

Figure 4-3. The continuum of geothermal energy technology applications and uses [56].

Resources for geothermal energy vary by location and are ultimately dependent on the source temperature and depth, rock chemistry, and the abundance of ground water [61]. Heat from molten rock, or magma, beneath the Earth's surface is captured in reservoirs of water-saturated rock. These resources require penetration of the Earth's surface in order to characterize, access, and efficiently extract the heat energy. This requires geologists to dig exploratory wells into the reservoirs and pipe the hot water or steam into a power plant for electricity production; in areas of high geothermal potential, production wells and power plants must be dug and built [55]. Building these power plants and their necessary cooling towers takes up a considerable amount of land, and the exploration, drilling, and plant construction may be a months-long process requiring considerable logistics support. Additionally, profitable geothermal development requires that heat reservoirs be close enough to the Earth's surface such that they can be accessed by drilling wells into the saturated rock layers. Loss of heat and pressure from the heated fluids after they have reached the surface poses a significant challenge, as the energy disperses quickly through transportation.

Because of the challenges associated with transporting heated fluids without the loss of energy, geothermal energy is usually converted into electricity by power plants located at the well site and then the resultant electricity transmitted for use elsewhere. Geothermal resources can be used directly, rather than to generate electricity, if a need exists near the well site. In such direct use applications, hot water from the reservoir is used to provide heat for industrial processes, greenhouses, crop drying, heating buildings, and even melting snow on sidewalks and bridges [62] [63]. The heated water from below the surface is brought up through the well, and a mechanical system (which may include piping and pumps, a heat exchanger, and controls) delivers the heat directly for the intended use. Since commercial geothermal resources must be considerably close to the surface (for economic reasons), their infrastructure is most often built in areas of high geological activity, where magma may be close enough to the surface and the tectonic plates are either moving apart or colliding, such as the "ring of fire" of the Pacific Rim. Most U.S. domestic resources, therefore, are found in the western continental United States, as well as Alaska and Hawaii [56] [64].

4.2.2 Geothermal Resources

Three major categories of geothermal resources include geothermal heat pump (GHP), hydrothermal, and enhanced geothermal systems (EGS), which support a range of applications for both electric and non-electric energy production (Figure 4-4).

Geothermal heat pump resources exist in the shallow-earth environment where ground temperatures are relatively constant year-round (7°C to 21°C), and the soil, rock, and/or aquifers present a significant geothermal energy source due to their thermal storage properties; this enables them to function as a heat-exchange medium for low-grade thermal energy [56] [65]. The shallow-earth's thermal storage capability provides a heat sink in the summer and a heat source in the winter to increase the efficiency and reduce the energy consumption of heating and cooling applications in buildings. Shallow-earth resources exist across all fifty states and can be used for GHPs wherever the ground can be cost-effectively accessed to depths below seasonal temperature variations.

Hydrothermal resources occur in a diverse range of geological settings, sometimes without clear surface manifestations (volcanoes, fumaroles, hot springs, or geysers) of the underlying resource. These systems naturally contain the fluid, heat, and rock characteristics – such as open fractures that allow fluid flow – necessary to generate electricity (or to be used in direct use application if a need exists nearby). Unlike GHP resources, hydrothermal resources vary in temperature significantly, ranging from a few degrees above ambient conditions to temperatures over 375°C. Temperatures above this higher range require a new class of production technologies to extract the resource's geothermal energy.

Enhanced geothermal systems are unconventional geothermal resources that are similar to hydrothermal resources, but differ in the fact that they do not naturally possess the groundwater or rock characteristics necessary for energy extraction. Enhanced geothermal systems are man-made reservoirs, created where there exists an abundant heat source, but insufficient fluid to carry the heat or limited pathways to conduct fluid through the hot rocks [66]. The inability to accurately predict reservoir characteristics such as temperature and permeability in both hydrothermal and EGS alike poses a significant exploitation risk, and a new class of innovative production technologies such as subsurface characterization and imaging are necessary in order to efficiently convert geothermal energy resources for beneficial use with minimal or no modification required to existing power-plant technologies.

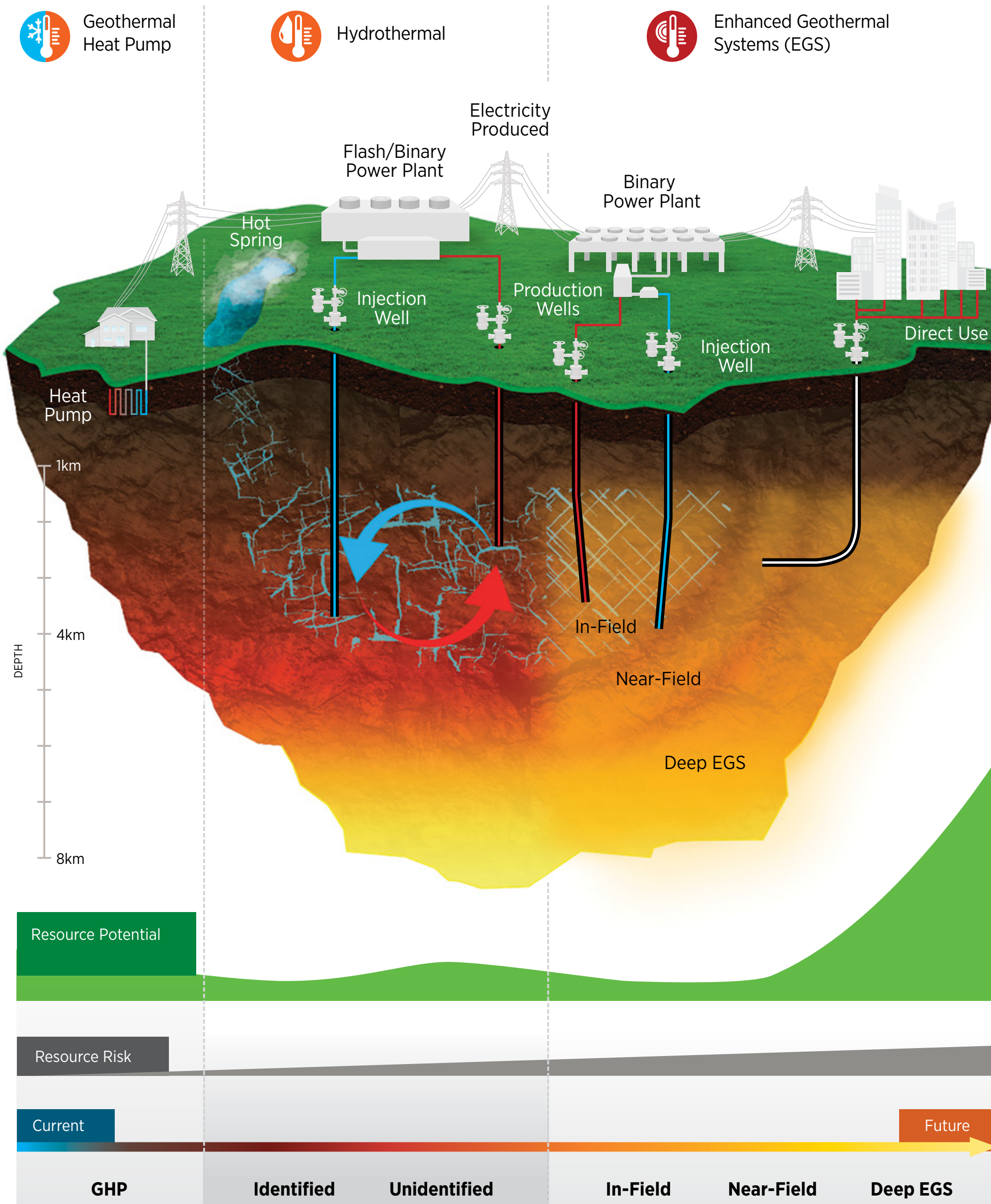

Figure 4-4. The diversity of geothermal resources and applications, delineated within three resource categories: geothermal heat pump, hydrothermal, and enhanced geothermal systems [56].

Advances in technology may mitigate the challenges associated with the geothermal exploitation process. For example, remote sensing may be able to replace the need for geologists on the ground and automated and hybrid drilling may reduce the logistics and time needed to drill wells. Fracture mapping and fluid qualities could help reduce the uncertainty of drilling and enhance heat transfer capabilities. Discovering more useful ways to utilize waste heat would also reduce the reliance on cooling towers and increase the overall efficiency of the power production process. Any of these advances also would assist in the application of geothermal energy for everyday use [56] [64] [67].

4.3 Emerging Technologies

The geothermal industry and the oil and gas industry use similar technologies and methods to locate and drill for sources of energy; however, the characteristics of these sources may vary substantially. For instance, oil and gas reservoirs tend to exist under higher pressures than geothermal reservoirs, but at significantly lower temperatures. The technology and intellectual capital transfer between the two industries can be bidirectional, despite variations in resource environment and market size between them, reducing cost and risk for both. Several advancements in geothermal technologies can be attributed to the adaptation of oil and gas technologies to conditions beyond their original technical limits. Similarly, the oil and gas industry has benefited from adapting technologies sourced from geothermal energy. The most notable example of geothermal technology transfer to the oil and gas industry is the research, development, and commercialization of polycrystalline diamond compact drill bits. This innovation catalyzed the growth of a $1.9 billion industry and produced significant cost savings for the oil and gas industry [56].

Cost, particularly in enhanced geothermal systems, poses a significant barrier to the expansion of geothermal energy exploitation, as its advancement requires a new class of innovative production technologies. For example, reducing the costs of casing and cementing deep EGS wells can be achieved through expandable tubular casings, low-clearance well casing designs, casing while drilling, multilaterals, and improved penetration rates. These developments will dramatically improve the economics of deep EGS wells. Concepts relating to casing design have been successfully used in the oil and gas industry, and are easily adaptable to fit the needs for EGS. The first three concepts, which relate to casing design, are widely used in the oil and gas industry and can easily be adapted for EGS needs [68].

4.4 State of the Art

In April 2020, the Department of Energy (DOE) announced the availability of up to $25 million in funding through the Geothermal Technologies Office to promote the advancement of EGS technologies and techniques. These grants support research and development (R&D) that complements DOE's Frontier Observatory for Research in Geothermal Energy (FORGE) initiative and aligns with the goals of the GeoVision study, which outlines a path to unlock the full potential of geothermal power. The research to be funded will focus on the areas of *Pilot* – preparing and repairing existing wells, as well as hosting the testing of innovative downhole tools and well stimulation technologies in parallel with or in preparation for deployment at the FORGE site – and *Amplify* – testing and validating targeted stimulation techniques for improving productivity of wells or increasing inter-well connectivity at existing geothermal fields for purposes of producing additional energy [56] [66].

Additionally, the Geothermal Technologies Office of the DOE announced selections for up to $10 million in Integrated EGS R&D to twelve collaborative EGS R&D projects that will use novel techniques to increase the precision and accuracy of measuring critical underground reservoir properties over time. These project teams will focus on the integration of a variety of cutting-edge, complementary technologies and approaches in order to optimize the development and sustainability of EGS reservoirs. Table 4-1 provides information on the twelve geothermal project teams selected for DOE funding [69].

Table 4-1. U.S. DOE funded EGS R&D project descriptions [69].

Awardee	Location	Project Description	DOE Share
Array Information Technology	Greenbelt, MD	Array Information Technology will develop an integrated approach to assess the flow of injected fluid during EGS resource development. Array will monitor the system prior and during EGS injection, evaluate the fracture density and dimensions, and determine the fluid flow velocity in the activated fracture network.	$591,666
California State University Long Beach	Long Beach, CA	California State University Long Beach plans to evaluate hydraulic connectivity among geothermal wells using Periodic Hydraulic Testing (PHT). The principle is to create a pressure signal in one well and observe the responding pressure signals in one or more observation wells to assess the permeability and storage of the fracture network that connects the two wells.	$449,994
Cornell University	Ithaca, NY	Cornell University will develop and test a chemical tracer procedure for modeling reservoir structure and predicting EGS thermal lifetime. If successful, this will provide reservoir operators with the ability to evaluate proposed reservoir management practices and to quantify the probability of successful deployment, including cost.	$475,836
Lawrence Berkeley National Laboratory	Berkeley, CA	Lawrence Berkeley National Laboratory plans to develop a three-dimensional fluid transport model using radon in order to better characterize fractures in geothermal reservoirs. LBNL will use the amount of radon in the water to calculate the size of the fracture the water travels through, a critical EGS parameter.	$915,663
Lawrence Berkeley National Laboratory	Berkeley, CA	Lawrence Berkeley National Laboratory plans to model and simulate an integrated technology using geophysical methods in combination with injection of carbon dioxide for purposed of well monitoring. The technology is designed to characterize fractured geothermal systems.	$749,000
Los Alamos National Laboratory	Los Alamos, NM	Los Alamos National Laboratory will develop high-precision characterization techniques to model fluid-flow pathways in EGS reservoirs. This research will provide high-resolution, high-accuracy 3D models, and produce high-resolution images of fracture zones in EGS reservoirs. If successful, this research will provide a new technology for mapping and characterizing fluid-flow pathways in EGS reservoirs.	$3,000,000
The Pennsylvania State University	University Park, PA	Pennsylvania State University will explore ways to assess both the characteristics and evolving state of EGS reservoirs prior to stimulation and during production. The project will help scientists analyze the permeability of reservoir fracture networks in order to understand evolving flow structure and to engineer thermal recovery systems.	$197,000
The Pennsylvania State University	University Park, PA	Pennsylvania State University will focus on the processes governing fracture flow and energy production in EGS reservoirs and examine methods to manage and predict changes in permeability over their lifetimes. This will be accomplished by measuring properties of reservoir rocks to study the mechanisms of fluid-induced permeability and to develop acoustic methods to image fracture characteristics.	$769,267
Sandia National Laboratories	Albuquerque, NW	Sandia National Laboratories will develop a system of nanoparticle-based chemical tags for EGS reservoirs. The gradual release of the unique tags will mark both the location of the reservoir and flow rates for above-ground assessment. This previously-unavailable information will provide engineers the ability to closely monitor many subsurface flows simultaneously, leading to production efficiencies, and will provide for longer term monitoring without interfering with active wells.	$800,000
University of Nevada, Reno	Reno, NV	University of Nevada, Reno will use a technique to detect interference between pairs of seismic signals in order to gain useful information about the subsurface. Existing and newly acquired seismic survey data will be used to compare data from this cost-effective, non-invasive, seismic exploration method with data from a comprehensive geoscience study of the geothermal system in Dixie Valley, Nevada. This proposed technology has the potential to enhance the ability to characterize subsurface fracture, stress and other physical reservoir properties at a variety of geothermal fields.	$408,195
University of Oklahoma	Norman, OK	University of Oklahoma will integrate several techniques for characterizing full-sized EGS reservoirs under realistic stress and temperature conditions, including simultaneous monitoring of acoustic emissions, fluid flow tracers, and changes in reservoir pore pressure and fluid/rock temperature. The proposed work will provide essential data and information to understand induced fractures, and will help improve reservoir performance.	$880,000
University of Wisconsin-Madison	Madison, WI	University of Wisconsin-Madison will assess a technology for characterizing and monitoring changes in the mechanical properties of rock in an EGS reservoir in three dimensions. The integrated technology will analyze data including seismic waveforms, ground deformation, specialized radar, and comparisons of well pressure, flow, and temperature to characterize the reservoir.	$2,999,973

Engineers have also begun to address the high cost of well construction through the development of a high-temperature downhole motor that provides a high-power downhole rotation solution for directional drilling. The current commercially available downhole motors, for example Positive Displacement Motors, are reliant on elastomeric material, which limits operations in high temperatures and renders them unreliable for extended use in the hot, rocky environment of geothermal wells. Proprietary advanced materials are being developed that will endure prolonged exposure to high temperature and pressure. This novel motor allows for downhole directional control when drilling high temperature formations, resulting in preferential targeting of geothermal resources, a considerable advancement from the conventional drilling technologies. It can also drill wells with multilateral completions, resulting in improved geothermal resource recovery and well construction economics, thus significantly contributing to the development of geothermal power into a more affordable alternative energy source. Additional applications for high-torque linear motors have also been conceived [70].

4.5 Impact on DoD Energy Needs

In 2010, the Defense Advanced Research Projects Agency (DARPA) sponsored a workshop to investigate the development of geothermal energy technology for use by the U.S. military [64]. The workshop concluded that alternative sources of energy such as geothermal, that can be used in a theater of operations (for example as at a forward operating base (FOB)), would have high military value if they could substantially reduce the logistics requirements of transporting conventional energy there without imposing large logistics costs. Additionally, energy from sources other than the power grid would be valuable at fixed installations because they would reduce reliance on that grid. A large renewable energy source on Guam would be timely and valuable because of the planned move of tens of thousands of military personnel there, because the island government is seeking to add renewable energy capacity, and because water purification may one day be needed to augment the island's water supplies. Successful exploitation of geothermal energy on the island could provide sufficient power to desalinate seawater and augment the island's water supplies, thus avoiding the need to drill twenty-two new water wells and putting less pressure on the existing aquifer. The ability of such sources to purify water at a FOB would further increase their value because of the high cost of transporting water in theater. The most relevant solutions from a DoD perspective likely are the advancement of EGS, particularly through improvements in sensor and automation technologies, and the means to increase the efficiency of geothermal power production while decreasing its footprint. Other, more immediate applications for military purposes, such as ground source heat pumps and geothermal power on Guam, appear to be matters of investigation and assessment than of technical progress, though advances in the technologies associated with these applications would be helpful and render them more attractive than otherwise [71].

The *2016 DoD Operational Energy Strategy* implementation is guided by specific initiatives and goals, including the objective to "Identify and Reduce Logistics and Operational Risks." One goal under this initiative is to diversify energy supplies, including using renewable energy sources at the point of need in order to reduce the burden of resupplying operational forces with liquid fuel. Particularly, technologies that enable the utilization of locally available energy are of interest. The DoD stated that they will examine opportunities to increase the use of "energy harvesting" technologies that collect energy from the environment or surrounding area in order to reduce the need for resupply. Thus, geothermal power has the potential to be an asset to the DoD, especially after further technological advancements [1] [2].

5

Ocean Thermal Energy Conversion

5.1 Introduction to Ocean Thermal Energy Conversion

Ocean Thermal Energy Conversion (OTEC) is the use of the temperature difference between ocean water at the surface level and at the deep level in order to produce power. A basic requirement of an OTEC plant is that the surface level water and the deep level water have a temperature difference of 20°C, which would theoretically (if operating at 100% efficiency) produce 0.0214 kwh per kg of warm seawater, as seen in Equation 5-1.

Equation 5-1.

$$Q = Cp * \Delta T$$

$$Q = 3850 J/kg*°C * 20°C$$

$$Q = 77000\ J/kg$$

$$Q = 0.0214\ kwh/kg$$

Where Q = Energy Heat, Cp = Heat Capacity(J/kg*°C), ΔT = Temperature Difference(°C)

The 20°C temperature difference limits OTEC usage to those areas shown in Figure 5-1.

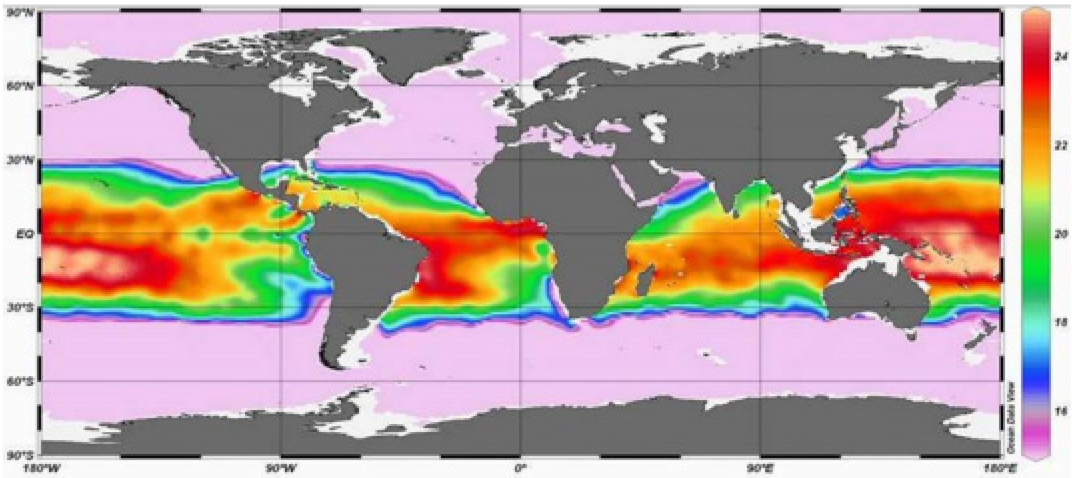

Figure 5-1. Ocean temperature differential between depths of 20 meters and 1000 meters [72].

Figure 5-2 shows the OTEC process, which begins as one of two feed pipes brings in cold water from the deep ocean (typically from depths greater than 1000 m). The other pipe brings in warm water from the surface of the ocean. Within the system, there is a third pipe that contains a volatile liquid, otherwise known as the working fluid. Simlar to the geothermal plant, the temperature of the surface water vaporizes the volatile liquid and the resultant gas vapor is then fed through a turbine. The gas turns the turbine, producing electricity. The vapor is then cooled and condensed by the lower-temperature deep water, and this cooled water is released back into an ocean through an outlet pipe. This cycle is continuous, meaning that power is constantly being produced by ocean water drawn from the environment (Figure 5-2).

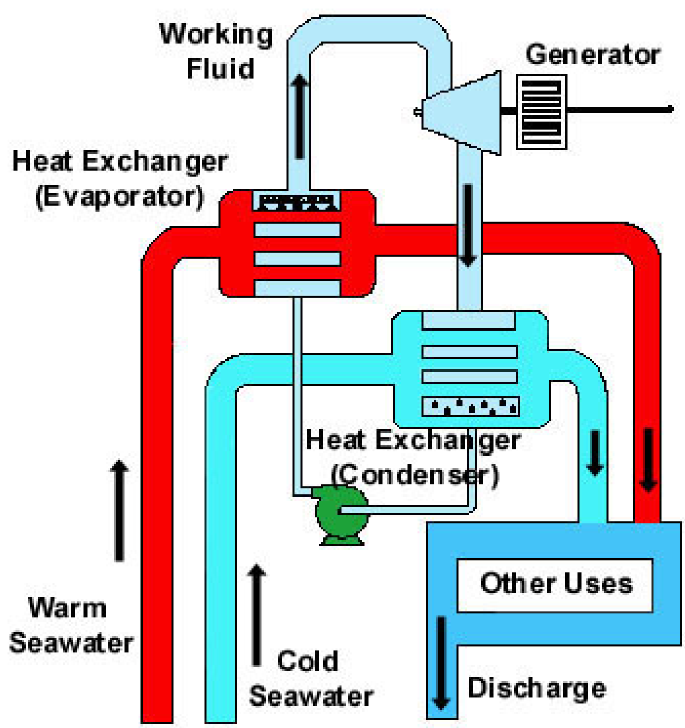

Figure 5-2. A Schematic of an OTEC plant [73].

5.2 History of OTEC and Current Technology Uses

5.2.1 The Original OTEC

The idea of using the thermal energy of the ocean dates back to the 1880s with Jacques-Arsene d'Arsonval, a physicist and medical doctor. D'Arsonval is known for his work in the field of electrophysiology and the founding the field of electrotherapy, the use of electric currents for medical purposes. He also invented the thermocouple ammeter and the D'Arsonval galvanometer. In 1881, he proposed tapping into the thermal energy of the ocean [74].

In the 1930s, a student of d'Arsonval, Georges Claude, produced the first operational version of an OTEC system. Georges Claude was an engineer and inventor who was well known for devising industrial processes that are still in use today. These include the production of neon lighting and the well-known process for the liquification of air in the industrial production of liquid nitrogen, oxygen, and argon [75]. The original design of the OTEC plant as designed by Claude did not include the volatile fluid that is vaporized and condensed, but rather used warm and cold water from the ocean. This method of power production is known as an open loop OTEC plant, as opposed to the modern version, known as a closed-loop OTEC plant.

In an open loop plant, the water from the surface is evaporated by reducing the pressure in a tank that the water is fed into. This creates a vapor that is then fed into a turbine to produce power. In order to keep the pressure in the chamber low so that the surface water will keep evaporating, the vapor is condensed by a pipe containing cold water from the deep ocean; after the thermal energy has been harvested, the condensed water is taken out of the system as show in Figure 5-3. When the water is evaporated, it leaves behind its salt content, giving the added benefit of producing pure fresh water. Georges Claude created his OTEC plant in Matanzas, Cuba, and it was capable of producing 20 kW of energy along with a supply of fresh water from ocean water. This 20kW of energy is sufficient to power fifteen modern homes continuously [76].

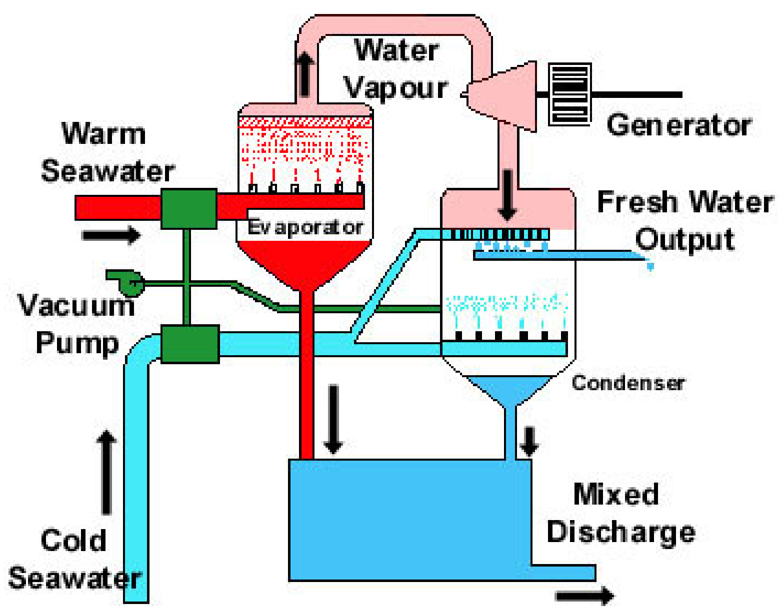

Figure 5-3. A diagram of an open-loop OTEC plant [73].

5.2.2 1970s, 80s, 90s

During the 1970s, U.S., Japanese, and Russian scientists independently began researching OTEC technology for a variety of reasons, but mainly resulting from a sharp increase in oil prices and the resultant impact on the world economy. This research led to a key advancement in OTEC technology, the modern day closed-loop system, which helped to reduce energy waste by using an intermediate (working) fluid. A Russian scientist named Alexander Kalina was able to create an ammonia-water mixture that improved the efficiency of the system developed by Claude. The introduction of a mixture of ammonia and water as the volatile fluid allows it to boil over a range of temperatures as opposed to only boiling at one temperature. When forced to boil at a single temperature, energy used to bring the fluid close to its boiling point without reaching it is wasted. If allowed to boil over a range of temperatures then none of the energy will be wasted. A mixture of water and ammonia, yields boiling range of -33.34 °C to 100 °C thereby preservingheat energy. This enables the system to extract more of the energy from the heat source, yielding a more efficient energy generation process. This system, known as the Kalina cycle, is mainly used in industrial applications such as steel, coal, and oil refineries in order to harness energy from the heat, but is also applicable and applied to OTEC [77]. In 1979, U.S. scientists were able to create a mini-OTEC plant that ran for three months. This plant was located on a boat 2.2 km off the coast of Hawaii, showing that OTEC plants could be located at sea as opposed to being stationed on land, thereby eliminating the need for longer pipes running from land to the sea floor [78].

5.3 Case Study: Makai Facility

The Makai facility, located in Hawaii, is an OTEC research facility funded by the U.S. government, primarily by the DoD and the DOE (Figure 5-4) [86]. The main focus of this facility is to research the heat exchange networks, which are a key component of this type of energy generation. As heat exchangers make up approximately one-third of the cost of an OTEC plant [79], any reduction in the cost of the heat exchanger, whether by improving the efficiency, reducing the size, or extending the life cycle, will drastically improve the economics of large-scale OTEC plants. One of the main heat exchanger efficiency research topics concerns the fluid used as the thermal conduit; the fluids being tested at this facility include refrigerants such as ammonia, R-134a, and Freon.

Figure 5-4. The Makai OTEC Plant (Source: Makai Ocean Engineering) [80].

In addition to heat exchanger research, the facility has also developed a device for the construction of the necessary deep-water pipe. A key issue in the construction of OTEC plants is in the manufacturing of the deep-water pipes due to the depth and associated logistics burden of assembling a long and large pipe. The device developed at the Makai facility consists of two grippers; on gripper that holds the pipe in place while being welded together, and a second gripper that lowers the pipe deeper into the ocean (as seen in Figure 5-5 [81]).

Figure 5-5. Device developed to produce deep-water pipes (Source: Makai Ocean Engineering) [80].

The Makai test system has also been connected to the local power grid and can be used to power 120 homes in the local town (100 kW of power), using an ammonia-based fluid in the heat exchanger network. This specific plant has intake pipes of 40 inches in diameter, while a 10 mega-watt (MW) plant would require intake pipes of 13 feet in diameter. The reason for the increase in diameter is that the power production is proportional to the amount of water being processed by the plant, as seen in Equation 5-1.

5.4 State of the Art

5.4.1 New OTEC Plants

There are currently two OTEC plants in operation, the first of which is the previously discussed Makai project in Hawaii. The second plant is located in Okinawa, Japan; completed in 2013, the Okinawa plant is capable of producing 100 kW of electricity (the same amount of energy produced at the Makai project). The OTEC plant design in Okinawa has the potential to produce 2,797 MW of power with a complete off-shore plant [82].

Recently, a floating plant was constructed in Tamil Nadu, India with a 1 MW design capacity. The plant ultimately failed due to a problem with the construction of the deep-water pipe [83]. This is a common problem, typically due to the high pressure and the depth at which the pipe has to be assembled. The Makai OTEC plant offers a potential solution to this problem with the gripper system that was developed, as discussed in Section 5.3.

Additionally, plants are being considered in the Maldives and are intended to generate enough power for the islands' resorts. Such plants could replace the diesel engines that are currently used to power all the resorts in the area, thereby reducing the amount of pollution currently generated. Using existing technology, the OTEC plants available for construction are capable of producing up to 1 MW of electricity, which would be enough for any island resort located there [84] [85].

5.4.2 Current Technology

Working Liquid: The volatile liquids typically used in OTEC systems must have two properties: a low boiling point (less than the surface water temperature) and be environmentally friendly (i.e. if the fluid accidentally mixes with the returning water stream, it will not be harmful to the ocean). Traditionally, the working fluid in OTEC plants is a refrigerant such as R744, ammonia or R-134a. Research in the efficiency of the volatile liquids is currently being conducted at the Makai plant.

Deep Water Pipe: One of the main problems encountered in constructing an OTEC plant is the deep-water pipe. As seen in the Indian plant construction, a problem with the construction of the deep-water pipe is what led to its eventual failure. At the Makai plant, researchers have been testing a method of creating and lowering the deep-water pipe into the ocean for an offshore 10 and 100 mega-watt (MW) OTEC plant. This method uses two grippers that hold the pipe in place and slowly lower it as additional sections of pipe are welded onto the end [81] (Figure 5-5).

Cost: Another drawback of a power plant based on OTEC technology is that the initial construction cost is higher than a traditional plant relying on diesel generators. Overall, the price to run an OTEC plant is 42 cents per kWh and for a 1 MW plant and 22 cents per kWh for a 10 MW plant. In comparison, a 1 MW diesel generator costs around 21 cents per kWh assuming a cost of three dollars per gallon of diesel (discounting shipping costs of diesel fuel to the generator location).

5.5 Impact on DoD Energy Needs

The DoD has funded several OTEC technology research efforts, including the Makai facility. The primary service that will benefit from OTEC technology will be the Department of the Navy, as the technology can most readily be used for island bases throughout the United States Indo-Pacific Command's area of responsibility and for bases in the littorals (Figure 5-1).

It can easily be seen that OTEC is an ideal technology to support power needs in these locations for a variety of reasons. As ocean water is the fuel source for OTEC plants, the plants will not need a continuous supply of fossil fuels to operate, while proximity to the ocean allows it to economic access to an abundant supply of the necessary water. Further, the volatile or working fluid will operate in a closed-cycle, so it will only need to be replaced or "topped up" infrequently, and it can be made to be environmentally friendly.

An advantage of an OTEC over other forms of alternative energy that DoD is pursuing, such as solar and wind, is its relative independence of weather conditions. The temperature of the deep ocean does not fluctuate heavily, so an OTEC facility will not need to rely on backup generators to produce power except in an emergency. OTEC is primed to power naval bases in the Pacific, Atlantic, and Indian Oceans along with helping the naval services reduce their dependence on fossil fuels.

6

Nuclear Energy

The 2016 Defense Science Board Task Force on Energy Systems for Forward/Remote Operating Bases reported that "[n]uclear power sources could offer a compelling alternative for the production of electrical energy to employing either conventional fossil fuels or alternative energy sources for military applications [87]." Although nuclear energy derived from fission is not a renewable energy source and does not meet the strict definition of an alternative energy source due to its hazardous radioactive spent fuel, it is otherwise a clean source of energy that does not pollute. The National Security Strategy recognizes the important role that nuclear has as one of the abundant energy resources that contribute to clean, affordable, and reliable energy in the United States. In discussing the energy resources of the United States, it states that our "sources of clean, affordable, and reliable energy underpins a prosperous, secure, and powerful America for years to come [88]." A discussion of nuclear energy is included in this state of the art report specifically because of renewed interest by the DoD for using nuclear power to provide electricity in austere or remote locations, which will be discussed later in this section. Nuclear fusion will also briefly be discussed; although it is not currently an alternative energy source, research does continue into its potential use.

6.1 Introduction to Nuclear Energy

The power of the atom can be harnessed in two different ways to create energy. The first method is via fission, or the splitting of atoms. Nuclear power plants across the globe use nuclear fission to generate electricity, specifically from the splitting of uranium atoms using a neutral particle (i.e. a neutron). The second method to create nuclear energy is via fusion, or the combining of atoms. Fusion requires tremendous pressure to overcome the inherent property of atomic nuclei to repel each other, due to the positive charge of the proton(s) that make up the nuclei of atoms. Fusion is the process by which the sun burns its nuclear fuel in its core. The sun's massive gravity provides the necessary pressure to overcome the repulsive forces of the positively-charged hydrogen nuclei. Figure 6-1 depicts the process that occurs in fission and fusion reactions.

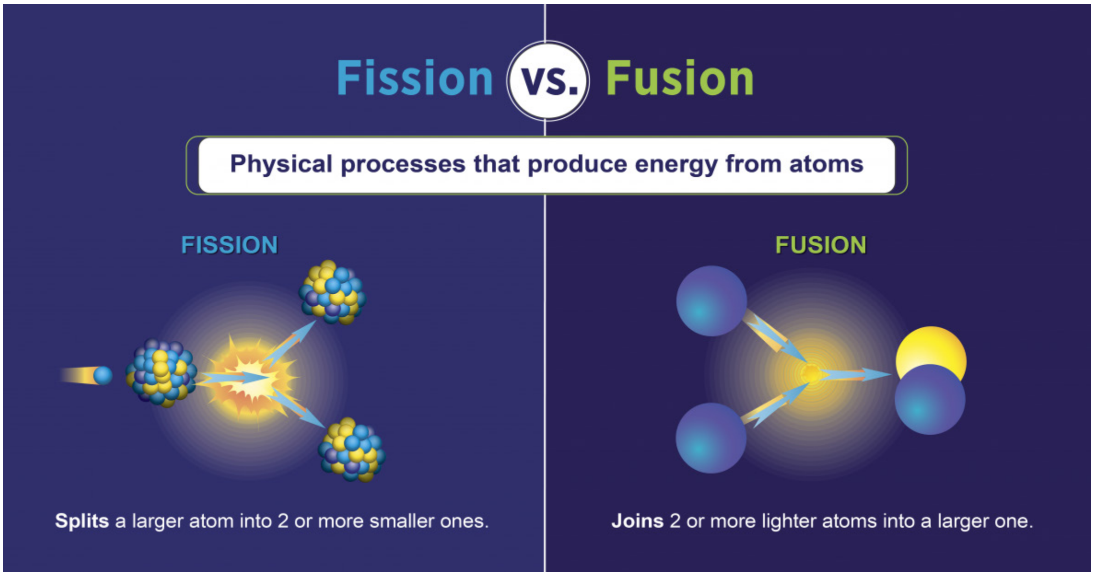

Figure 6-1. Fission and Fusion Reactions [89].

As with many other fuels used to generate electricity, in particular fossil fuels such as coal, natural gas, and diesel, nuclear energy makes use of heat generated in its processes to turn turbines, which in turn spin generators to produce electricity. For nuclear energy, this heat is generated by the fission process of splitting atoms. However, unlike the burning of fossil fuels, the fission of nuclear fuel does not create any greenhouse to gases, and the splitting of a uranium atom produces "nearly one hundred million times the amount of energy as the burning of one carbon atom in a fossil fuel [90]", again without the impact of greenhouse gas-producing emissions.

The first commercial nuclear power reactor went online in the United States and began generating power for the electric grid in 1958 when the reactor at Shippingport Atomic Power Station in Shippingport, PA began operations [91]. At its peak, U.S. power utilities operated 104 nuclear reactors located at 64 nuclear power plant sites. Today, 96 reactors are in operation at 58 power plant sites in 29 states [92]. At the end of 2019, nuclear energy accounted for 55 percent of the carbon emission-free electricity generated [93] and 20 percent of all energy produced [92] in the United States. In comparison, France relies on nuclear energy to produce more than 70 percent of its electricity. Table 6-1 provides a list of select countries and the share of energy generated by nuclear power in those nations. As of July 12, 2020, there are 440 nuclear power reactors in operation in 30 countries around the world, with an additional 54 reactors under construction [94].

Table 6-1. List of Select Nuclear-Power Generating Countries [92].

Country	Nuclear Energy's Share of Total Electricity Generated
China	3.7%
Russia	18.4%
United States	19.8%
South Korea	26.6%
France	71.5%

6.2 History of Reactor Technologies

The two reactor technologies used in the United States are the pressurized water reactor (PWR) and the boiling water reactor (BWR). Both are considered light-water reactors (LWR) in that they use light water as both a coolant and neutron moderator. Another common feature of both technologies is the use of a steel reactor pressure vessel (RPV) that contains the fuel. Every nuclear reactor essentially operates the same way when generating electricity, i.e. raising the temperature of liquid water to generate steam that is used to ultimately turn a generator in the cycle. The PWR technology does so using a two-loop system so that the water being heated by the fission process is not the same water than is turned to steam and used to turn the turbine (Figure 6-2). The heated water from the RPV travels through the first loop to a steam generator, where water in the second loop is turned to steam. The BWR technology turns water to steam using a single-loop system, with the water heated by the reactor to the point that it boils to form steam within the RPV itself, which is then used to turn the turbine (Figure 6-3). After the steam passes through the turbine, both technologies then condense the steam to liquid water and it returns in its loop to the RPV (in the case of the BWR) or the steam generator (in the case of the PWR) in a continuous cycle while the reactor is operating. Figure 6-2 and Figure 6-3 also show how excess heat is removed from the power plant through the use of cooling towers.

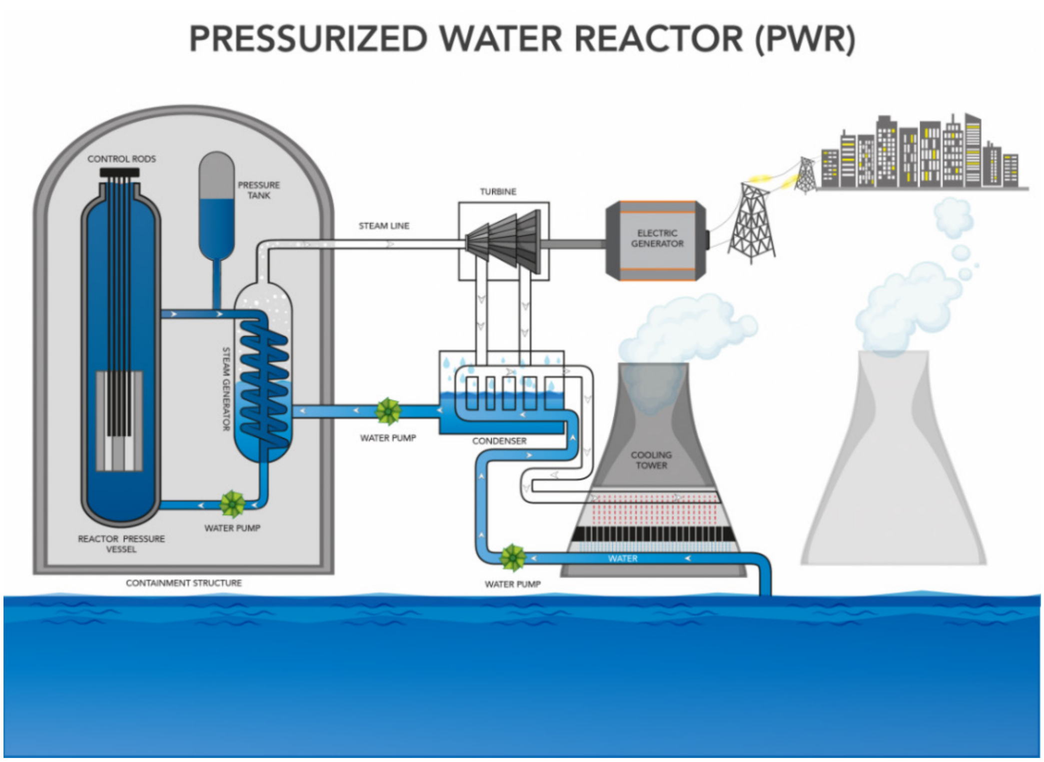

Figure 6-2. Pressurized Water Reactor (two-loop system) [95].

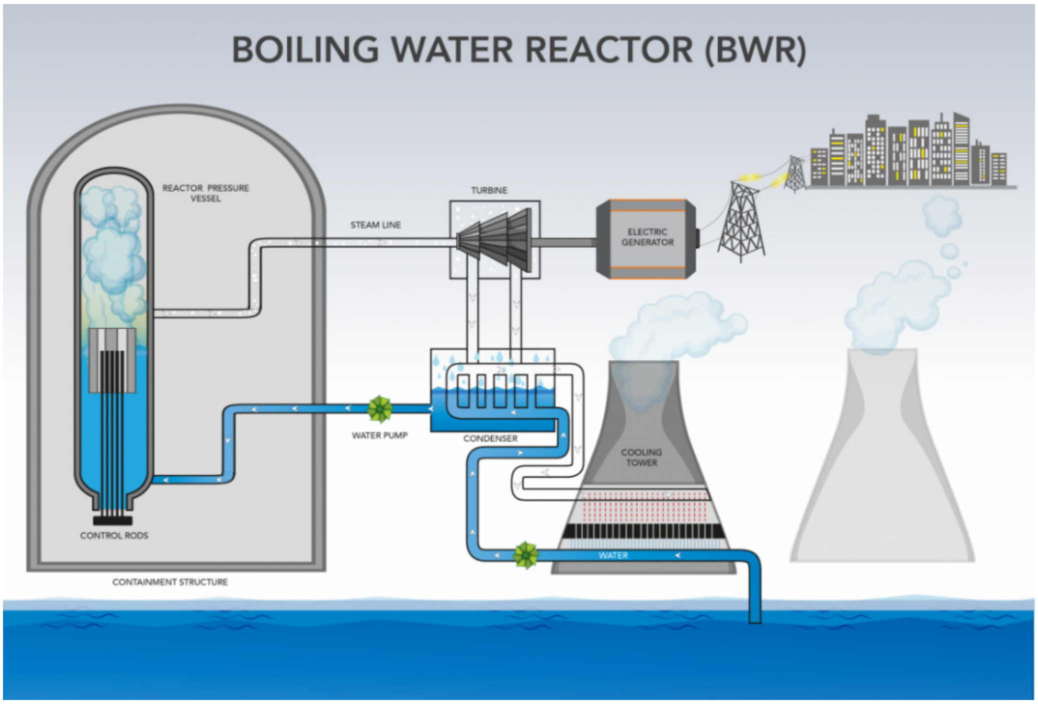

Figure 6-3. Boiling Water Reactor (single-loop system) [95].

The benefit of the two-loop system found in the PWR is that it allows for containment of radioactive water inside the containment structure, and prevents radioactive contamination of the condensor, and other equipment in the second loop. A benefit of the one-loop system in the BWR is its simpler design that reduces the equipment needed, most notably the steam generator.

6.3 Safety Concerns Associated with Nuclear Energy

Although considered a clean fuel in that it doesn't contribute greenhouse gases to the atmosphere, nuclear fission does have radioactive fission products in the spent nuclear fuel that must be dealt with and will be discussed later in this section. By contrast, nuclear fusion, although still not a viable source of energy on Earth, would eliminate the hazardous waste impact that is present with nuclear fission. Nuclear fusion, as seen in our Sun, creates energy that does not generate radioactive fission products.

A a result of well-known accidents at Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011), there have been and continue to be well-founded concerns about the safe operation of nuclear power plants. Each of these three accidents will be discussed briefly to provide a background on the cause of the accidents and the amount of radiation released.

The Three Mile Island (TMI) Nuclear Power Station is located near Harrisburg, PA. The power station was comprised of two PWRs. The accident occurred on March 28, 1979 at the TMI unit 2 reactor, and the Nuclear Regulatory Commission (NRC) characterized it as a loss of coolant accident (LOCA). The accident started when a pressure relief valve malfuctioned [96]. The condition was made worse when operators failed to properly diagnose the problem. The resulting coolant loss in the reactor pressure vessel exposed the upper portions of the uranium fuel assemblies to extreme heat (generated by the radioactive decay of the fission products in the fuel assemblies), resulting in the fuel melting from the heat and flowing down through the core before re-solidifying. Even though the fuel melted, very little radioactive material was released to the atmosphere because the containment vessel was not breached [97]. It is estimated that the total amount of radiation released from non-noble gases was less than 150 curies (Ci) [98]. Although Unit 2 has been in a non-operating status since the accident and the fuel has been removed from the RPV, Unit 1 at the TMI nuclear power station remained in operation until September 2019.

The Chernobyl nuclear accident occurred on April 26, 1986 in Ukraine. The nuclear power station was comprised of four identical RBMK (*Reactor Bolshoi Moschnosti Kanalynyi*, Russian for Channelized Large Power Reactor) reactors, a uniquely Soviet design that was not used by other countries. It is a graphite-moderated, light water-cooled design. The Union of Soviet Socialist Republics (USSR) developed this design by scaling up the design of the graphite reactors they used for weapons-grade plutonium production as part of their nuclear weapons program [99]. The primary motivation for the USSR to design their power reactors based on the graphite reactors used in plutonium production was driven by cost at the expense of safety [100]. At the time of the accident, operators at the plant were performing a safety test to validate the design of the RBMK reactor. The plant operators theorized that in the event of a blackout at the plant, "the inertia of the now freeflowing, electricity-producing turbines could be used to maintain coolant flow until the emergency generators came online to operate the coolant pumps [97]." To test this theory as part of the safety test, the plant operators needed to turn off automated safety systems (something that can not occur in U.S.-designed reactors). Because of the inherently unstable design of the RMBK reactor, the reactor's power level began accelerating while carrying out the test. To stabilize the reactor's power as needed, the operators inserted the control rods, but due to the design of the control rods, the reactor experienced a significant power surge. In the span of about four seconds "the power level of the reactor reached 100 times full power, resulting in vaporization of the pressurized cooling water, leading to a steam explosion that blew the concrete cover plate off the reactor core [97]." This was followed by a second explosion as a result of the hydrogen that formed. It is estimated that the total amount of radioactivity released from non-noble gases was 143 million Ci [98].

The Fukushima Dai-Ichi Nuclear Power Plant is located on the eastern coast of the main Japanese island of Honshu. The power plant was comprised of six BWRs, with three of the reactors operating at the time of the accident. On March 11, 2011 a tsunami trigged by an earthquake off the coast of Japan struck the nuclear power plant. As a result of the earthquake and prior to the arrival of the tsunami, plant operators had begun the necessary shutdown procedures at the plant. Cooling pumps were operating properly to remove the residual heat generated by the decay of the radioactive fission products. The tsunami, reaching a height of 14 meters, breached the six meter seawall of the power plant, knocking out all power at the plant, including back-up generators. Over the next several days several hydrogen explosions, resulting from the super-heated water corroding the fuel elements and generating the hydrogen gas, sent contamination into the surrounding area [101]. Although the Fukushima disaster involved more reactors than Chernobyl, the Fukushima disaster is considered to not have been as big a disaster as Chernobyl. The Nuclear Energy Institute, as recently as October 2019, stated that the Chernobyl accident released about ten times the radiation of the Fukushima disaster [102].

Despite these three well-known accidents, there are more than 400 reactors being safely operated around the world on a daily basis. A Congressional Research Service report characterized the U.S. nuclear energy's safety in comparison with other major commercial energy technologies as "excellent [103]."

Even when a nuclear power plant operates normally year after year, the eventual safe disposal of spent nuclear fuel is an important issue that needs to be addressed. Spent nuclear fuel "is used fuel from a reactor that is no longer efficient in creating electricity, … however it is still thermally hot, highly radioactive, and potentially harmful [104]." The United States currently does not have an operating national respository for spent nuclear fuel. Instead, each of the power utilities is responsible for storing their reactors' spent nuclear fuel on site [105]. The NRC requires that the used fuel is first put into wet storage (spent fuel pools), see Figure 6-4, for cooling of the initially highly-radioactive fuel, and then in dry storage to allow for air cooling of the fuel, see Figure 6-5.

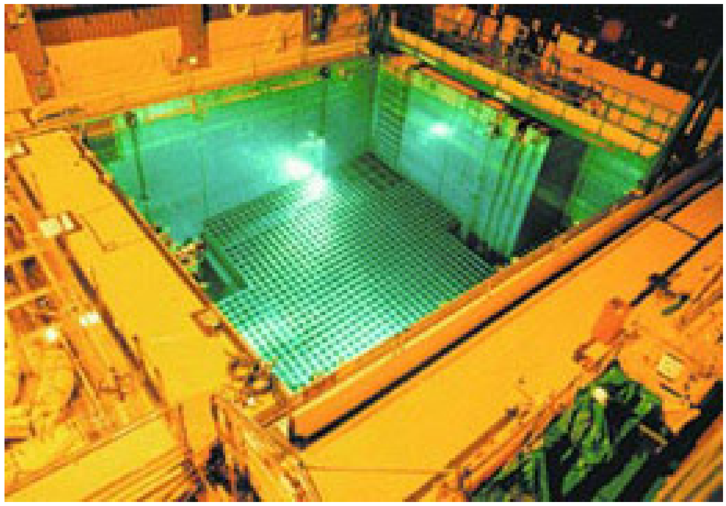

Figure 6-4. Spent Fuel Pool [106].

Figure 6-5. Dry Storage Casks [107].

In addition to the concern presented by the harmful radioactive nature of used nuclear fuel, there is also the concern of proliferation of fissile materials. One of the by-products created by the fission of the uranium fuel is plutonium, which can be removed from the used nuclear fuel to develop a plutonium-fueled nuclear weapon. The chemical process of removing the plutonium, and other useful material from the used nuclear fuel such as any remaining uranium, is extremely hazardous, and is not undertaken without risk.

6.4 Small Modular Reactors

The International Atomic Energy Agency (IAEA) defines a small modular reactor (SMR) "as a reactor with an output of 300 megawatts electric (MWe) or less [108]." For comparison, each reactor at Three

Mile Island was rated at just over 800 MWe, Chernobyl reactors were rated at 1000 MWe, and each reactor at Fukushima Dai-Ichi rated at just under 800 MWe. Small modular reactors, and a subset of them, the very small modular reactor (VSMR), offer several benefits that can assist the DoD in meeting its energy resiliency goals. Table 6-2 lists the benefits of SMRs that make them a viable power source for DoD use.

Table 6-2. Benefits of Small Modular Reactors [108].

Carbon-free baseload power	Integration of renewables
Enhanced safety	Siting flexibility
Modularity	Lower total capital cost
Small land requirements	Process heat
Scalability	International export opportunities
Improved energy security	Reduced fuel risk

The DoD has a long history of developing and operating small reactors. Since the lauch of the nuclear-powered USS Nautilus submarine in 1954, the Navy has used nuclear reactors on a daily basis in its submarines and aircraft carriers (as well as cruisers previously) to provide power, heat, and propulsion. Additionally, the Army developed a number of mobile and portable reactors in the 1960s to provide power in austere and remote locations, including Greenland and Antartica [109].

In support of a decision to seek the deployment and employment of mobile nuclear power plants using vSMR technology, the Army G-4 (Logistics) released a study in late 2018 advocating for nuclear energy as a cross-cutting enabler of military power to the force. Specifically the study analyzed the "benefits and challenges of mobile nuclear power plants (MNPPs) with [vSMR] technology and to address the broader operational and strategic implications of energy delivery and management [109]." The study outlined six viable options for the use of MNPPs by the Army:

- Fuel logistics and storage of Class III [fuel] curtails CCDRs [combatant commanders] options, increases complexity, and/or imposes substantial economic challenges.
- Infrastructure requires large-scale power (e.g. ports, airfields, rail, other transportation supporting infrastructure, industry etc.).
- Mission assurance is required or where "islanding" is desirable (providing continuous power to a location even though energy from an electrical grid/'external power source is no longer present).
- Energy intensive systems (e.g. forward radar site operations) require significant power.
- Power is desired to support defense support to civil authorities (DSCA).
- Access to an established or stable electric grid is unavailable or where the electric grid requires reinforcement or reconstitution to support intermediate staging bases, logistics staging areas, and/or medium to large base camps.

The study recognized the unique regulatory and licensing requirements of nuclear power, and points out the experience the Army and the DoD have already with nuclear power and working with the regulatory offices at the DOE, the NRC, and the Department of Transportation.

6.5 State of the Art

6.5.1 SMR Technology

In March 2020, the DoD's Special Capabilities Office (SCO) let a contract authorizing three companies to design and develop small modular reactors [110]. The mission of the SCO is "to develop new and innovative ways to shape and counter emerging threats across all domains, bringing unexpected and game-changing capabilities to the Joint Force [111]." The contract was awarded under Project Pele [112], and the companies selected by DoD were BWX Technologies, X-energy, and Westinghouse. Each of these companies has experience in the nuclear power industry and is familiar with the necessary regulatory and technology requirements that have to be met. The DoD is coordinating this effort with the necessary regulatory agencies, which include the DOE, NRC, and the National Nuclear Security Administration [110]. It is a significant step in the furthering of SMR technology that may one day be used to meet the operational and installation energy requirements of the DoD. The three companies selected have been given two years for the design phase. Following this phase, the SCO is expected to select one company to build and demonstrate their prototype. The objective of the Project Pele will be to "design, build, and demonstrate a prototype mobile nuclear reactor within five years [112]."

6.5.2 Nuclear Fuel Technology

Nuclear energy has been operating as a clean and reliable source of power for the U.S. electric grid since 1958. With the move to SMRs, new nuclear fuel technologies are being developed that can take advantage of their benefits. One of the innovations are the fuel elements that would reduce or even eliminate the concerns of spent fuel undergoing radioactive decay and causing extreme heat and leading to a meltdown (e.g. as happened during the TMI and Fukushima accidents when cooling water was no longer available). One of the more promising advances is the develop of the Triso fuel element.

Triso fuel, short for tristructural isotropic, uses low enriched uranium for fuel and is surrounded by layers of graphite and a ceramic [113]. Each fuel element is smaller than a poppy seed. The design allows the fuel element to withstand a tremendous amount of heat, including the normal operating temperature of the reactor and also the heat from radioactive decay of the fission products when the reactor is in a shutdown status (e.g. undergoing maintenance, or being moved to a new operating site).

The advancement of Triso fuel leads to the ability to design smaller reactor facilities. The Triso fuel element "carries its own containment" in its design, and can result in a reactor "that fits in a cargo container and still [have] all the safety features of a traditional commercial reactor [113]." Some proposed SMR designs are able to operate for two years or more without needing to be refueled [114].

6.6 Impact on DoD Energy Needs

The DoD recognizes that climate change has national security implications and should make a commitment to the reduction of greenhouse gases [115]. The DoD can have a significant role in pursuing new reactor technologies, in particular those of SMRs. The design that the DoD pursues will not only benefit the Department, but could also become the model for commercialized systems first in the United States and also marketable to other countries. The SCO, by having three companies participate in the design phase of developing a mobile nuclear reactor, is taking the lead in developing the technologies that can later be used in the commercial industry. The use of SMRs and vSMRs has the ability to reduce the DoD's need to burn fossil fuels. Their use will also contribute to reducing the need to transport fuel to bases, both fixed installations and facilities at home and abroad, as well as to operating bases in the CCDRs' areas of operation.

7

Conclusion and Future Needs for Alternative Energy

The *National Security Strategy of the United States (NSS)* and the 2018 *National Defense Strategy of the United States of America (NDS)* outline steps and goals that are clearly connected to the need for continued development of alternative energy sources. At the strategic level, secure energy sources are a key component of both American prosperity as well as the national defense. At the tactical level, alternative energy presents means and methods to lessen the logistics burden on forward deployed forces and simultaneously save lives.

The *NSS* recognizes that:

> *"Energy dominance—America's central position in the global energy system as a leading producer, consumer, and innovator—ensures that markets are free and U.S. infrastructure is resilient and secure. It ensures that access to energy is diversified, and recognizes the importance of environmental stewardship [88]."*

It goes on to say:

> *"The United States will continue to advance an approach that balances energy security, economic development, and environmental protection. The United States will remain a global leader in reducing traditional pollution, as well as greenhouse gases, while expanding our economy. This achievement, which can serve as a model to other countries, flows from innovation, technology breakthroughs, and energy efficiency gains… [88]"*

Finally, Pillar II of the *NSS* offers five priority actions under the step “Embrace Energy Dominance;” three of these five actions (Ensure Energy Security, Attain Universal Energy Access, and Further America’s Technological Edge) point directly to a need for the development of alternative energy resources.

Likewise, the *NDS* necessitates the continued investment in alternative energy resources in order to meet key capability and capacity needs. The *NDS* offers three distinct lines of effort, the first of which is to rebuild military readiness as we build a more lethal Joint Force. As part of that line of effort, the *NDS* prioritizes forward force maneuver and posture resilience. As such:

> *“Investments will prioritize ground, air, sea, and space forces that can deploy, survive, operate, maneuver, and regenerate in all domains while under attack. Transitioning from large, centralized, unhardened infrastructure to smaller, dispersed, resilient, adaptive basing that include active and passive defenses will also be prioritized [116].”*

The use of alternative and renewable energy sources is becoming more and more prevalent in the United States. The Energy Information Agency (EIA) projects that electricity generation from renewable resources as a percentage of all power sources will rise from 17 percent in 2019 to 20 percent in 2020 and 22 percent in 2021 [117]. Similarly, the DoD goal for installation energy produced by alternative and renewable energy sources is 25 percent by 2025 [2].

The DoD is not just the single largest consumer of energy in the federal government, but the largest consumer of energy in the United States [2]. Thus, it is vital that the DoD looks to increase its use of alternative energy sources and reduce its use of fossil fuels. Each of the DoD Components project that alternative energy sources will continue to contribute a greater share towards meeting its installation energy requirements. Specific statistics from FY18 (the year for which the latest data are available) include [2]:

- The Army adding 82.6 megawatts (MW) of capacity from alternative energy sources through 39 projects for a total of 517.6 MW
- The Marine Corps increasing its percentage for installation energy produced by alternative and renewable energy to 15.73 percent, up from 12.26 percent achieved in FY17
- The Navy exceeding the DoD goal for installation energy produced by alternative and renewable energy, achieving 29.42 percent
- The Air Force adding more than 100 MW of capacity from alternative energy sources, including solar arrays, landfill gas regeneration, and wind energy

As the DoD continues to increase its use of alternative energy sources and further reduce its reliance on fossil fuels, it will contribute to achieving its goal of increased energy security and resilience. And because DoD’s energy requirements are inseparable from its mission requirements, this will ensure the continued mission readiness of the armed forces.

Abbreviations and Acronyms

BWR .... Boiling water reactor
CCDR .... Combatant Commander
°C .... Degrees Celsius
Ci .... Curies
Cp .... Specific Heat
CSP .... Concentrating Solar Power
DARPA .... Defense Advanced Research Projects Agency
DC .... Direct current
DoD .... Department of Defense
DOE .... Department of Energy
DOT .... Department of Transportation
DSCA .... Defense Support of Civil Authorities
DTIC .... Defense Technical Information Center
EGS .... Enhanced Geothermal Systems
FOB .... Forward Operating Base
FORGE .... Frontier Observatory for Research in Geothermal Energy
GEO .... Geosynchronous
GHP .... Geothermal Heat-Pump
GHz .... Giga hertz
HDIAC .... Homeland Defense & Security Information Analysis Center
IAEA .... International Atomic Energy Agency
J .... Joules
Kg .... Kilogram
Km .... Kilometer
kW .... Kilowatt
kWh .... Kilowatt-Hour
LWR .... Light water reactor
MIT .... Massachusetts Institute of Technology
MNPP .... Mobile nuclear power plant
MSC .... Modular symmetrical concentrator
MW .... Megawatt

MWe........ Mega-watt electric
NASA........ National Aeronautics and Space Administration
NDS........ National Defense Strategy
NRC........ Nuclear Regulatory Commission
NREL........ National Renewable Energy Laboratory
NRL........ Naval Research Laboratory
OTEC........ Ocean Thermal Energy Conversion
PRAM FX........ Photovoltaic radio-frequency antenna module flight experiment
PV........ Photovoltaics
PWR........ Pressurized water reactor
Q........ Heat Energy
R&D........ Research and Development
RBMK........ *Reactor Bolshoi Moschnosti Kanalynyi*, Russian for Channelized Large Power Reactor
RF........ Radio frequency
RPV........ Reactor Pressure Vessel
SCO........ Special Capabilities Office
SMR........ Small modular reactor
SOAR........ State of the Art Report
SPS ALPHA........ Solar power satellite by arbitrary large phased array
STF........ Solar Thermal Fuels
STPV........ Solar Thermophotovoltaic Device
T........ Temperature
TMI........ Three Mile Island
USAF........ United States Air Force
vSMR........ Very small modular reactor

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