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GALLIUM ARSENIDE SOLAR CELLS ON UNMANNED AERIAL VEHICLES AND THEIR IMPLICATION IN THE MILITARY

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Abstract— *In recent years, the government and commercial market for Unmanned Aerial Vehicles (UAVs) has expanded. One of the most predominant limitations of UAVs is their flight time due to the restricted capacity of current batteries, resulting in a need to recharge UAVs too frequently. To address this issue, companies such as Alta Devices, which we will analyze in this paper, are utilizing highly energy-efficient gallium arsenide (GaAs) solar cells, an ideal power source for UAVs. The cells are extremely thin and flexible and can easily be affixed to any surface on a UAV. In this paper, we will discuss the advantages of GaAs solar cells compared to traditional silicon solar cells and show how these advantages make GaAs solar cells the most suitable choice for powering UAVs. Additionally, we will analyze the sustainability of GaAs solar cells in regards to their environmental and social impact. One practical use of such UAVs is in the military. We will explore the results of the research done by the United States Naval Research Laboratory, in which Alta Devices' GaAs solar cells were used to modify the company RnR's SBXC sailplane kit. By exploring the current use of weaponized drones in the military, we will discuss the possible implications of utilizing solar cells on drones in the military, how this modification is important to the future of the military, and the ethical issues surrounding the use of UAVs as military weapons.*

Keywords—drone warfare, gallium arsenide solar cells, military drones, solar power, unmanned aerial vehicles

INTRODUCTION: UNMANNED AERIAL VEHICLES AND THEIR PLACE IN THE MODERN WORLD

Since 2015, the market for drones has exploded after the Federal Aviation Administration granted hundreds of exemptions to different companies for drone use in areas such as aerial photography, surveying, and television production [1]. A drone is classified as an unmanned aerial vehicle (UAV), which is any type of aircraft that does not have an onboard human pilot. They can range in size anywhere from a few inches in length to almost 20 feet in length. UAVs are used for a multitude of purposes, ranging from aerial cinematography to personal use to use by the military, which will be examined in depth in this paper [2]. Considering how recently the market has grown, UAVs are still rapidly changing and improving in their design and function. Since batteries are currently being used to power UAVs, their most restrictive issue is their limited flight time due to battery capacity. However, additional batteries weigh UAVs down, shortening flight time further [3]. Thus, lightweight solar cells, or photovoltaic cells, are being implemented to provide additional power to UAVs, and possibly replace traditional batteries altogether.

Gallium arsenide (GaAs) solar cells, which are a type of highly efficient and lightweight solar cells made using semi conductive GaAs material throughout the cell, are a prime choice to power UAVs. They are extremely light and flexible in comparison to other solar cells, making them ideal for use on UAVs because they are easy to attach, and add little additional weight to UAVs [3]. Additionally, their high energy efficiency guarantees maximum power for UAVs [4]. By transitioning from traditional batteries to solar cells, future UAVs will be able to fly for longer periods, perhaps even indefinitely.

As solar cell technology progresses, it is important to consider the sustainability of the product. According to the 2012 Rio+20 United Nations Conference on Sustainable Development, "Sustainable development emphasizes a holistic, equitable and far-sighted approach to decision-making at all levels. It emphasizes not just strong economic performance but intragenerational and intergenerational equity. It rests on integration and a balanced consideration of social, economic and environmental goals and objectives in both public and private decision-making" [5]. Using this definition, we will analyze the sustainability of GaAs solar cells in regards to their environmental impact, as well as the social impact of how they are being used on UAVs.

GALLIUM ARSENIDE SOLAR CELLS: THE MOST EFFICIENT SOLUTION

GaAs solar cells are the best solution to maximize drones' flight time. Compared to their main competitor, silicon (Si) solar cells, GaAs solar cells prove to be advantageous in many areas, including efficiency, thickness, flexibility, and weather resistance.

Solar panel efficiency is measured by the percent of solar energy converted to electricity by a solar panel. GaAs solar cells are more efficient than Si solar cells, with records of 29.1% efficiency and 26.6% efficiency, respectively [4,6]. While this difference may not seem significant, there are many other implications to consider.

Record solar efficiencies are most often achieved in a laboratory setting, which means that the same technology will not necessarily be applicable in real world situations, most notably for their use on UAVs. Kaneka, a Japanese company most widely known for their use of chemical process to develop new synthetic materials, achieved the record 26.6% efficiency using Si solar cells, which measured about 160 micrometers in thickness [7]. However, the company's commercial products differ vastly from their products of research. Their commercial Si solar panels have a maximum 9.8% efficiency, with a thickness of four centimeters [8]. This is 250 times thicker than their experimental solar cells. Solar cells of this thickness are by no means suitable for use on UAVS – they are far too heavy, and lack flexibility. Comparatively, Alta Devices, a company based in California that studies and produces solar cells, achieved a record 29.1% efficiency using GaAs cells. The company develops products that are being put to practical use with efficiencies of 23%, nearing that of their record, at a thickness of only about one micron (one millionth of a meter) [6, 3]. Efficiency of solar cells is important in choosing the most suitable type of solar cell for UAVs, but physical characteristics of the cells, as briefly aforementioned, must also be reviewed in depth.

Physical Design of Solar Cells

Solar cells are planar devices that are used to harness the energy of the sun and convert it to electricity. They capture the energy of small quantities of light called photons using partially conductive materials called semiconductors, such as GaAs or Si. The process of energy capture will be discussed in further depth later. Since many different semiconductors exist that are utilized in solar cell production, it is ideal to choose one that is both efficient and has a good physical design. Thickness and flexibility are important considerations when choosing a solar cell to use on UAVs. Since the goal of using solar cells is to prolong flight time, it is most advantageous to use the slimmest solar cells, as they will add the least mass to the UAV. Adding heavy solar cells would weigh the UAV down, decreasing flight time and running contrary to the original goal [3]. Not only are thickness and mass important factors to consider, but also flexibility. Flexible solar cells are important because they are easier to affix to the curved surfaces of UAVs, which are common to make UAVs more aerodynamic. Flexibility comes with very thin solar cells; hence, these cells are advantageous due to their low mass, small width, and flexible design. Figure 1 shows a thin, flexible GaAs solar cell from Alta Devices.

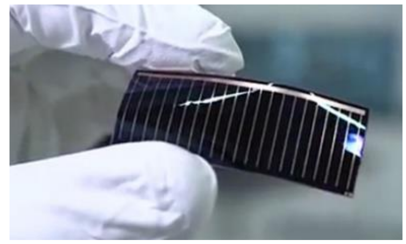

FIGURE 1 [9]
Flexible solar cell produced by Alta Devices

On the contrary, installing non-flexible solar cells would be problematic on a curved surface. For example, when affixing Si solar cells to their SBXC Sailplane, the Naval Research Laboratory cut the cells into thirds to best attach them [3]. While mechanical design and implications of the solar cells with respect to UAVs is important, another crucial aspect is their weather resistance, since their use will be primarily outdoors.

Nature is full of many obstacles for solar cells, most notably ultraviolet radiation, wind, and sunlight. Solar cells overheat at high concentrations of sunlight, causing them to lose efficiency [10]. Thus, materials with low thermal conductivity are the best choice for solar cells because heat travels through the cell at a lower rate. Consequently, they remain at a lower temperature, making them more efficient than another cell at the same concentration of sunlight with a higher thermal conductivity. GaAs has a thermal conductivity of 45 $Wm^{-1}K^{-1}$, compared to 130 $Wm^{-1}K^{-1}$ for Si solar cells [10]. Its lower thermal conductivity makes it more resistant to heat and sunlight outdoors. It has been shown that GaAs solar cells are highly energy efficient, although the specific reasons for this efficiency are more complicated.

PHOTOVOLTAIC CELLS AND PHOTON RECYCLING IN GALLIUM ARSENIDE

How Do Solar Cells Work?

To understand why GaAs solar cells are so efficient, it is important to understand how any solar cell functions. As aforementioned, solar cells utilize photovoltaic technology, in which light is converted into energy by semiconductor materials. Semiconductors are nonmetal materials that have a conductive quality in between that of an insulator, which cannot conduct electricity, and a conductor, which conducts electricity very well (like metal wires used in electronics). The production process of solar cells can vary based on factors such as thickness (conventional home solar panels are much thicker than Alta Devices' GaAs solar cells) and material. In the case of Alta Devices' GaAs solar cells, production involves a complicated chemical process. First, a process called Metal-Organic Chemical Vapor Deposition (MOCVD) is used to deposit thin layers of GaAs film onto a thicker base called a wafer, also made of GaAs [9]. They are separated by a layer of another material that will be destroyed when the film is removed from the wafer. To peel the GaAs film from the wafer, a process called Epitaxial Lift Off (ELO) is used. In ELO, hydrofluoric acid is used to remove the sacrificial layer, thus separating the GaAs film and wafer [11].

After the solar cells is produced, it can be used to generate electricity. Since energy is captured from sunlight, solar cells are considered to produce renewable energy. According to the U.S. Energy Information Administration, renewable energy, or clean energy, is "energy from sources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time" [12]. Thus, solar cells are sustainable in a literal sense that the energy they capture is limitless, and can be sustained forever, helping generations to come. Additionally, in regards to the previous definition of sustainability from the 2012 Rio+20 United Nations Conference, solar cells are sustainable because they fulfill environmental goals to harness more clean energy. The alternative to clean energy is nonrenewable energy, which is limited and when depleted cannot be replenished quickly. The main source of nonrenewable energy is fossil fuels, which are made from dead plants that were compressed by heat and pressure over millions of years [12]. When they are burned, they produce carbon dioxide, which traps heat in the atmosphere, contributing to climate change. Thus, solar cells are sustainable because they replace environmentally harmful sources of nonrenewable energy by capturing safe, unlimited energy provided by sunlight.

The conversion of light to energy occurs when semiconductor materials like GaAs absorb photons of light. If the photon has a high enough energy of impact, it separates electron-hole pairs that exist within the semiconductor. If electrons separate from their holes, they can be captured as an electric current. However, if recombination of the electron-hole pair occurs, the energy of this electron cannot be utilized as electricity. In more specific terms, the simplest solar cells (single junction solar cells) consist of both a p and n region, with p on the bottom of the cell and n on the top. As seen in Figure 2, light travels from top to bottom of the cell to the p region. The energy from the photon causes an electron-hole pair to separate, sending the electron toward the junction between the p and n layer. If the electron travels across the junction to the n layer without recombination occurring (this means the photon had high energy), its energy can be captured [13].

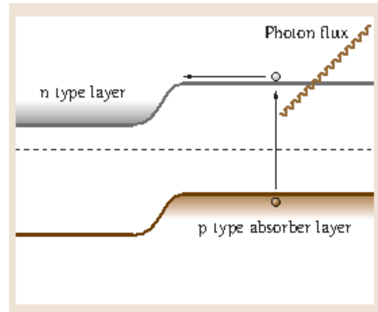

FIGURE 2 [13]
Photons from light create electric current

Photovoltaic cells can be either single-junction or multi-junction. Figure 1 shows a single junction solar cell, in which there is one n type layer and one p type layer separated by a single junction. The Shockley-Quessier limit for conversion efficiency defines the maximum efficiency that a single junction solar cell can theoretically achieve, though this limit has never been reached. According to this limit, the highest efficiency that a single junction solar cell can achieve is 33.5% [14]. On the other hand, multi-junction solar cells have many more layers of material and multiple junctions, as seen in Figure 2, which allows for higher solar efficiencies of over 45% [15].

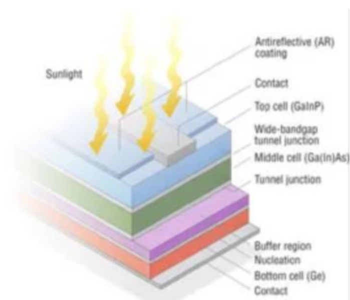

FIGURE 3 [12]
Structure of multi-junction solar cell

However, multi-junction solar cells are more expensive to produce due to the materials used to produce them and the complex process of joining so many layers. They are currently produced mostly by researchers aiming to lower costs of multi-junction cells, but they are also being used for space applications [13]. Consequently, Alta Devices produces single junction GaAs solar cells. To create solar cells of maximum efficiency, Alta Devices is utilizing the process of photon recycling within their single junction solar cells [9].

Photon Recycling

As previously stated, the maximum efficiency of a single junction solar cell is 33.5% [14]. Though this efficiency was determined in a study published in 1961, it is still widely cited and virtually universally accepted. Efficiencies typically fall below this due to factors such as recombination. However, by using a process called photon recycling, solar cells can compensate such factors. After photons are absorbed by a solar cell, they are emitted back into the environment when they escape through cone shaped holes in the surface of the solar cell. However, if they are reflected to the previously discussed p type absorber layer, they can be reabsorbed in the cell. Reabsorption of the photons, or photon recycling, allows the same photon to separate multiple electron-hole pairs, thus generating more energy in the solar cell. Photon recycling is currently done using flat planar back mirrors on the far side solar cell, which reflects a photon back into the p type absorber layer until it escapes out of a cone in the surface of the cell [16]. In addition to back mirrors, antireflective coating (ARC) on the front surface traps photons in the cell. While the name may be misleading, ARC prevents external reflection of photons off of the solar cell before they even enter, thus ensuring that photons pass into the solar cell. After they are in the solar cell, ARC causes internal reflection of photons in a similar manner to the back mirror [17]. 100% photon reflection is assumed in the calculation of 33.5% maximum efficiency of a single junction solar cell. Figure 3 shows 100% reflection of a photon until it escapes from a cone in the surface.

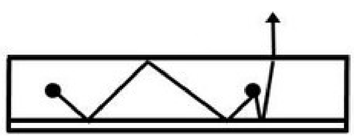

FIGURE 4 [17]
Reflection of a photon within a solar cell

By the process of photon recycling, Alta Devices has developed record efficiency single junction GaAs solar cells. Due to their efficiency, size, flexibility, and weather resistance, Alta Devices' solar cells are an optimal choice to power a UAV. Due to the aforementioned reasons, the Naval Research Laboratory utilized Alta Devices' solar cells to power one of their own UAVs.

THE NAVAL RESEARCH LABORATORY'S SBXC SAILPLANE

To examine effect of solar cells on flight endurance of UAVs, the NRL modified the model SBXC sailplane kit from RnR products. The wings were custom built and tested solar cells from five different companies of varying materials. Most significantly, the NRL outfitted one set of wings with Alta Devices' solar cells, and another set with the company Sunpower's Si solar cells to test the flight endurance of the UAV. Alta Devices' solar panels had an efficiency of 23%, while Sunpower's Si solar cells had an efficiency of 22%. It should be noted that Alta Devices achieved a record 29.1% efficiency in December of 2018, while the results of the testing was published in 2017 [6]. Thus, Alta Devices' GaAs solar cells were only 23% efficient at the time of the study.

The UAV itself weighed 6.8 kg, and required 70 W of power to fly. It was controlled by a custom-designed battery pack and controller. The battery pack weighed 1.91 kg [3]. This adds a significant amount of weight, weighing 28% of what the UAV itself does. It is easy to see that replacing the battery pack altogether in the future would be beneficial not only by providing power, but also by decreasing the weight of the UAV. With only the battery pack, the UAV could fly for about 4 hours [3]. Additionally, replacing the battery pack with solar cells would decrease toxic waste cause by batteries. Batteries contain toxic chemicals and metals, including cadmium, nickel, manganese, mercury, lithium, and acids (cadmium and nickel are known human carcinogens). Disposed batteries undergo a photochemical reaction, emitting greenhouse gases. They can also pollute water and soil, which effects nearly all forms of life as contamination is passed up the food chain [18]. Replacing batteries with solar panels would be more sustainable by reducing the amount of toxic chemicals in the environment, which also reduces the risk of harm of animals and people who may be exposed to toxic food or water. This is true not only in regards to batteries used on the SBXC sailplane, but batteries in general.

Assembly

To test the solar panels, they were assembled onto custom built wings that produced a final wingspan of 4.5 meters. Sunpower's Si solar cells had to be cut in thirds using a dicing saw before they were assembled onto the wing, since they were not flexible. The wing was constructed in two halves, each weighing 211 grams, for a total weight of 422 grams. At 22% efficiency, the wing produced up to 84 watts of power under AM1.5G conditions. This is an industry standard used to test solar cells, with specific conditions including a 25°C cell temperature and irradiance of 1000 watts/square meter (irradiance is a measure of how much power from sunlight reaches the surface of a solar cell) [19]

Unlike Sunpower's Si solar cells, Alta Devices' solar cells are flexible, so they did not have to altered before attachment to the wing. When describing the assembly of the UAV wings, the conductors of the testing at the NRL wrote that the wing using Alta Devices' solar cells "was the easiest of all wing assembly builds" [3]. Figure 5 shows Alta Devices' solar panels laying completely flat against the curve of the wing, due to their flexibility.

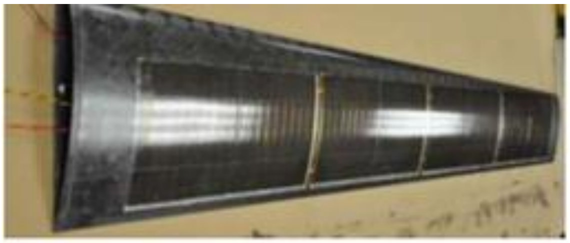

FIGURE 5 [3]
UAV wing constructed with Alta Devices' solar cells

This further proves that flexibility is an important quality of solar cells to consider, and it makes Alta Devices' GaAs solar cells more advantageous and desirable for use on a UAV. Ease of build is significant if UAVs are being used for practical applications. The more difficult UAVs are to build, the longer it will take to do so. Not only are Alta Devices' solar cells flexible, but they also weighed less than Sunpower's Si solar cells. The wing was again constructed in two halves weighing 158 g each, for a total weight of 316 g. This is about 25% less mass than that of the wing constructed using Si solar cells. The wing generated 92 watts of power under the same AM1.5G test conditions [3]. If the latest solar cells were used, this power would be even higher due to greater efficiency [6]. Alta Devices' GaAs solar cells produced more power than Sunpower's Si solar cells. Although the difference in power is not extreme, the GaAs solar cells were lighter and more flexible than the Si solar cells.

Testing the Wings

Both the UAV using wings constructed Alta Devices' GaAs solar cells and SunPower's Si solar cells were tested for endurance of flight. The UAV with SunPower's solar cells flew for 10.9 hours. The solar cells provided a maximum power of about 80 watts. The flight had two periods of soaring, meaning that the motor was not running. Thus, it was not using power from the battery, so the battery cold recharge during this period. The solar panels provided 353 watt-hours (this is a unit of energy), while the battery supplied 357 watt-hours. On the other hand, the UAV constructed with Alta Devices' GaAs solar cells flew for 11.2 hours, and provided a maximum of 101 watts. Unlike the first UAV, this one did not have any periods of soaring, so no additional power was provided. It is estimated that the UAV using Alta Devices' solar cells could have flown for at least 1 hour longer if it had soared, like the UAV using the SunPower solar cells. Even so, Alta Devices' solar panels provided 587 watt-hours, while the battery supplied 320 watt-hours [3]. Alta Devices' GaAs solar cells provided more energy than SunPower's Si solar cells and allow the UAV to fly for longer periods if soaring conditions are the same. Alta Devices' solar cells proved once again to be the best solar cells to use on a UAV based on flight endurance, weight, flexibility, and ease of build. Further, the solar cells also work in less ideal weather conditions. The endurance tests were performed when it was mostly sunny, but the solar cells still function in overcast conditions. In a shorter 1.59-hour test flight when it was overcast, Alta Devices' solar cells provided 73.5 watt-hours, while the battery provided 38.3 watt-hours [3]. Even in poor weather conditions and lower amounts of direct sunlight, the solar cells still provided almost twice the amount of energy that the battery did. All in all, GaAs solar cells are an excellent choice to power UAVs. The goal of the research was to work toward a 24/7 information, surveillance, and reconnaissance (ISR) mission, in which information about the enemy is gathered by observing their activity and movement [20]. Constant ISR would be possible if UAVs in the military could fly indefinitely. Research and development of GaAs solar cells is making this goal plausible as flight endurance of UAVs increases with new technology.

CURRENT USE OF DRONES IN THE MILITARY

History of UAVS in the Military

Though the NRL conducted research concerning the future of UAVS in the military, they have existed in the military for over a century. Beginning in the early 20th century, the US Army began developing aerial torpedoes to be used as weapons of war. The first model was named the Kettering Bug, and although the war ended before it was fully suitable for use, it sparked a revolution in military technology that continues today [21]. A major pitfall of the Kettering Bug was its autopiloted flight trajectory, so that once it began flying, its course could not be altered. Consequently, radio-control technology was implemented to remotely control UAVs in the military, similar to technology that exists today. In 1915 during WWI, Dr. Henry W. Walden, a dentist and member of the Aeronautics Society of New York, invented a radio-controlled rocket. This rocket was used to attack ground targets after its launch from the air [21]. An image of the early invention can be seen in Figure 6.

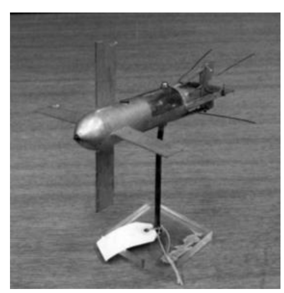

FIGURE 6 [21]
Radio controlled UAV developed by Dr. Henry W. Walden

Though Walden never received interest from the United States government, Germany used the first radio-controlled rockets in WWII.

As UAVs developed as weapons of war, they also found a new purpose in the military – surveillance. Drones took still images of battlefields in Vietnam, and later began carrying video cameras, which proved even more useful (the term drone is essentially interchangeable with UAV, and it is commonly used in reference to UAV use in the military). The Gnat, a UAV developed by the San Diego defense contractor, was the first to do this [22]. The concept of surveying from a bird's eye view was not new. However, previous to the attachment of cameras to UAVs, surveillance had to be done by pilots. Pilots need sleep, and aircraft needs significant amounts of fuel, making surveillance UAVs the superior option. Not only can they fly for longer periods of time, but they remove pilots from unnecessary danger.

The Gnat was remarkably successful, and was renamed the Predator. In fact, the Predator was so useful to the military that this was how Osama bin Laden was located in Afghanistan in 2000 [22]. He was already a known threat at the time, and airman Lee Ferran said that the United States had been searching for bin Laden for years [23]. At the time, surveillance drones were not weaponized, but this quickly changed after the September 11 attacks. Soon, Predator drones were armed with highly precise missiles called Hellfire missiles [22]. Thus, the world was presented with drones that served for both reconnaissance and attack – a deadly combination.

Military Drones Today

The Predator set the standard for military drones today. Drone use has increased exponentially, growing 1,200% in the United States just between 2005 and 2013 [24]. They developed even further so they can be controlled from anywhere in the world via remote operations providing live video to the operator, whereas the operator previously had to be on the ground near the drone. Drone operations in Afghanistan are piloted from as far away as Nevada by pilots who return to their homes daily, as if working a regular 9-5 job [25]. Like the Predator, military drones are most commonly equipped with highly advanced missiles, which are extremely precise and useful for hitting specific targets [26]. Thus, one primary use of military drones is the killing of specific targets, such as Osama bin Laden, as previously mentioned. Previous strikes were conducted by jet pilots. With jet pilots moving so quickly, discerning targets from civilians and fully absorbing their aerial view was difficult and ineffective in comparison to drone strikes [27]. With the introduction of military drones, aerial views can be studied for hours to fully absorb the situation, as the Predator can remain airborne for up to 40 hours [27]. An initial issue with the video provided by the Predator was the "soda straw" effect that came with it, in which operators had a limited scope of activity. Thus, surveillance technology was improved with sensor systems that underscored concerning areas of movement or weapons [27]. New camera technology allowed for a wider scope of a high-stake situation by drone operators.

While military drones are commonly used for individual attacks, they are also used in strikes against groups of militants of enemies. Drones are said to reduce the need for restrike against targets [26]. However, civilians have still been killed by drone strikes. In Yemen, the United States has been attempting to suppress al-Qaeda for over a decade. In 2018, it was estimated by the Associated Press that at least 30 of 88 people dead did not belong to al-Qaeda [28]. The killing of noncombatants raises legal issues concerning drone warfare.

Military drones are undoubtedly being utilized, but their use is legally still in a gray area. Under International humanitarian law, civilians are protected under law and should never be targets in war [29]. Thus, targeting a single person in a group of civilians may violate international law, and could be treated as a war crime. Because the highly weaponized drones that dominate the military today have such new technology, laws surrounding their use are still not definite.

A less questionable use of drones in the military that is expected to develop soon is delivering supplies to front lines. The Ministry of Defense, Department for International Development, and UK Research and Innovation launched a competition called the Autonomous Last Mile Resupply, which aims to deliver food, fuel, medical supplies, and any other necessary supplies to troops in a faster manner. It also reduces the amount of supplies that troops are expected to carry [30]. Regardless of the current debate of legality, drones are an important aspect of many modern militaries, especially that of the United States, not just as weapons but also for surveillance and tactical purposes.

HOW SOLAR CELLS WILL IMPACT DRONE WARFARE

As previously discussed, the use of drones in the military is rising at a rapid pace. As drone and solar cell technology continues to develop simultaneously, they will likely eventually be integrated. Solar cells will be vital to the future of high endurance military drones, which are in demand by the Air Force. In fact, the United States Air Force awarded the company Aurora Flight Sciences (a Boeing Company) $48 million to continue the development of a high endurance drone in 2018. The drone is called the Orion, and holds the world record for flight endurance at 80 hours [31].

With the installation of GaAs solar cells on military drones, flight endurance can be increased even further. In the case of the SBXC sailplane, flight time increased from 4 hours to 11.2 hours with the addition of GaAs solar cells, and it was estimated that flight could have even continued for an additional hour. While it is unclear how much flight endurance would increase due to different size and payloads without testing, solar cells would also increase endurance of military drones. It is unrealistic to assume that the flight time of a weaponized drone would increase to be almost 3 times as long, as was the case with the modified SBCX sailplane, due to the larger size of weaponized drones, and their heavy payload. For example, the SBXC sailplane had a wingspan of 18 feet and a no payload, while the Predator has a wingspan of 48.7 feet and can carry a payload of up to 450 pounds [3, 32]. However, drones used specifically for ISR missions, such as the RQ-7B Shadow may increase more due to a commonly smaller wingspan (20 feet) [33].

It is also important to recall that the theoretical maximum efficiency of any single-junction solar cell is 33.5% [14]. While this efficiency is unlikely to be sufficient in providing energy needed to indefinitely power such a large weaponized drone, multi-junction GaAs cells are also being researched, and have reached higher efficiencies of up to 45% [15]. Multi-junction cells have a higher capacity to increase in efficiency since their theoretical limit is around 66% [34]. Consequently, multi-junction GaAs solar cells would be considerably more effective in powering UAVS. However, they are more expensive, and this theoretical limit has not been reached. As such, the implications of single-junction solar cells should be predominantly considered.

By utilizing single junction GaAs solar cells on weaponized drones in the military, such drones will be able to fly for longer periods of time or carry larger payloads. Longer endurance is beneficial in many instances of military drone usage. Primarily, it is important to ISR missions because it would allow operators to survey situations for extended periods of time. By doing so, they can ensure that they have the right target, and fully understand how best to approach the situation. This would be beneficial to abiding by international humanitarian law, as it would allow militaries to determine if there is a risk of harming noncombatants. Additionally, although resupply drones do not yet exist, extending flight time and pay load of drones would allow these theoretical drones to carry more supplies over longer distances. This would enable supplies to be flown in from distances farther away from the dangerous front lines, thereby giving greater insurance that crucial supplies would reach military members. While these are not directly harmful scenarios, there could be a more fatal side to using GaAs solar cells on military drones. Increased payload and endurance may be used to carry supplies and perform surveillance, but they would also allow for more weapons to be carried over a farther distance. Doing so would create more dangerous weapons. In terms of weaponry, this would make drones more effective for military use since they could fly longer without refueling, and carry more missiles. The ethics of such dangerous weapons, however, is another issue.

ETHICS OF DRONE WARFARE

The proliferation of weaponized drones that would result from the installation of solar panels on them will also lead to a proliferation of the ethical dilemmas that already exist with this new form of warfare. Drones have benefited the military in numerous manners. Drones can fly much longer than manned aircraft, tend to be more cost effective, but most importantly, they remove the risk of pilots' lives. Drone operators are far from the drone themselves, so there is virtually no risk of operators being harmed [35]. Additionally, drone strikes are often designed to kill one target, so there should be significantly less casualties caused by drones than more traditional weaponry [36].

However, drone strikes are not realistically this ideal. They often pose a threat to non-combatants that are in proximity of the blast, which has can lead to unintended casualties. The claims that drone warfare do not harm innocent civilians are violated in several cases, which arguably violates international humanitarian law as well. To start, the most ideal situation, known as a personality strike, is when an individual of a terrorist group is sought out and targeted and only that individual is killed [36]. There are several incidences that run contrary to this claim. The first being an attack that occurred in Afghanistan where a convoy of families that stopped alongside the road was wrongly interpreted to be a group of terrorists. Among those killed were over a dozen children [36].

Events like this are likely the effect of a lack of definitive interpretation of aerial video and unavoidable prejudices that result from the dispatchment inherent to the job of drone operators. They perform another type of attack known as a signature strike, where people are grouped into categories and targeted based on behaviors that may be associated with terrorists. Under this notion, all military-aged men in combat zones are considered potential enemies [36]. It is also important to note that even under the personality strikes, which is done with the most scrutiny, targets are often misidentified, and other victims are killed instead. The human rights organization, Reprieve, asserts that, "each assassination target 'died' on average more than three times before their actual death," meaning that three other people were killed before the intended target [37]. This shows that U.S. intelligence regarding potential targets is not always reliable. It is also asserted that in Pakistan, from 2004-2013, 142 children were killed as collateral damage in the pursuance of 14 high value targets [37]. Considering this, it is easy to see that, as an unintended consequence, drones have become a terror weapon in their own right. Fear becomes a way of life for the villagers who are constantly circled by the drones and can hear the buzzing of the aircraft. Putting this information into consideration, the contrast between the conventional bombers before drones and modern drone warfare becomes less clear than it is often made to be. It may be that indiscriminate killing is unavoidable in war, regardless of how technologically advanced the weapon is.

With the increase in drone warfare, it is also important that its consequences on the drone pilots be acknowledged. It is understood that even though it is a remote experience, drone pilots view the battlefield with vivid resolution and are exposed to many traumatizing events. Some of these include watching civilians being tortured or killed by the enemy, others involve the killing of enemy combatants and surveying post-strike battle damage, which often involves the grief reactions of friends and loved ones [38]. Then, there is always the haunting possibility of collateral damage. Due to these causes, there is a PTSD rate of 6.51% for drone pilots [38]. With all this in mind, it is important that in the future, proper care be given to the drone pilots and the ethics of protocols are scrutinized so to minimize the negative effects had on drone operators and the civilians in war zones.

An understanding of the principles of sustainability can equip an engineer with the wisdom needed to make responsible choices related to these dilemmas. The aforementioned definition of sustainability applies here too, as military objectives must be balanced with societal, environmental, and humanitarian outcomes. More aggressive drone tactics may lead to more civilian casualties, but a more passive strategy may result in more civilians being killed by terrorists. Here, a thorough and inciteful cost-benefit analysis must be made in regards to the effects that drone strikes have on the society that finds itself in the war zone. The constant threat of attack from the sky can be highly damaging to the social fabric of a community, as people will become more isolated and avoidant of one another, fearing they may be identified as a target based on who they interact with. Also, the constant buzz of the drones above can lead to a more malignant environment that civilians have to live under, which is another important aspect of sustainability. On the flip side, there is also a need to sustain the mental health of the drone pilots and mitigate the effects that PTSD can have on them and their families. Sustaining humanitarian principles, which could be lost the in progression of drone technology, is of importance for future generations, as they may follow the example of present generations. Sustaining humanitarian principles is also of importance, which could be lost the in progression of drone technology. This is of relevance for future generations, as they are likely to follow the example of present generations. To minimize the negative effects in drone warfare, one needs to think sustainably, seeing through a broad viewpoint that acknowledges the positive and negative consequences that actions have across all people, society, and future generations.

CONCLUSION: UNINTENDED CONSEQUENCES OF TECHNOLOGY

There are several high-stakes decisions to be made that will affect a great many as drone technology continues to progress. The fitting of GaAs solar cells onto UAVs is one of many innovations that will ultimately lead to an increase in drone usage in the battlefield, and the countless dilemmas that will ensue. War in and of itself is an ethical conflict, so it is not definitive if weaponized drones themselves are overly harmful, or if they are simply a tool used in an inevitable larger conflict. Either way, it is imperative that ethics be considered as new technology develops so that in this new form of war, human morals are not impaired by these weapons. Not only that, but in a broader sense it is also important to consider the implications of any technology. While solar panels were not originally designed for the purpose of powering drones, it is clearly a major application that must be considered. Technology can help or hurt humankind, and it is vital that we do not abuse it.

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ACKNOWLEDGEMENTS

We would like to thank our writing advisor, Amanda Brant, for her guidance in writing our paper. We would also like to thank Judith Brink for her assistance in our research.