Feasibility Study of Utilizing Solar Panels to Power a Vehicle's Onboard Air Conditioner

by

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NOMENCLATURE

AC	Alternating current
Ah	Ampere hour
CFC-12	Freon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DC	Direct current
eV	Electron volt
ft^2	Square feet
GWP	Global warming potential
kW	Kilowatt
kWh	Kilowatt hour
m^2	Square meters
N_2	Nitrogen
NO_2	Nitrous Oxide
SF_6	Sulfur hexafluoride
SUV	Sport utility vehicle
V	Volt
VOC	Volatile organic compound
W	Watt

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ABSTRACT

The use of alternative energy technologies has become more prevalent as governments, corporations and individuals strive to reduce their carbon footprint. This report examines the feasibility of utilizing solar panels to gather energy to power the air conditioning system of three types of vehicles.

Solar cell technology was investigated to gain a more thorough understanding of the science behind how it works. Different types of solar cells were examined to determine their advantages and disadvantages.

The amount of solar energy available in Groton, Connecticut was determined. Next, the refrigeration cycle was explained, the automotive alternator was detailed and the size of three different vehicle's air conditioners were established. For each one of the vehicles, the usable area on the roof and hood was determined and used as the surface area for the solar panels.

The environmental impact of greenhouse gases was discussed and equivalent CO_2 ratings were given to some common components. Battery systems were discussed to store the energy produced from the solar panels.

Finally, the greenhouse gases that are generated by each vehicle during powering of its air conditioner are quantified Calculations are performed to determine how much energy could be produced by different types of solar panels on the available space on each vehicle. It was found that the energy which could be gathered by the solar panels is barely sufficient for two vehicles and insufficient for the third. The second scenario investigated utilizing supporting infrastructure such as solar panel canopies to gather energy and charge the car's onboard battery. The final scenario investigated roof and hood based solar panels with a backup alternator to provide energy during times when the solar panels could not produce sufficient energy.

The third scenario is the easiest to implement and provides the greatest flexibility while still reducing quantity of the greenhouse gases released into the atmosphere.

1. Introduction

1.1 Energy Sources

Global warming and the rising costs of petroleum products have become topics in the forefront of modern day science and politics. Research on renewable, non-fossil fuel energy technology has been steadily increasing and many consumers view these “green” energy technologies as opportunities to both reduce their carbon footprints as well as save money. Some examples of these energy sources that can be readily implemented in small-scale applications for the average consumer include solar, geothermal and wind energies. Other popular renewable energy sources, including tidal and hydroelectric, are not feasible or accessible for the average consumer.

Solar energy has become more appealing because of improvements in overall efficiency and decreasing costs. Currently, compared to the cost per watt of energy produced by coal, solar energy is more expensive; however, the cost of solar cells is continually decreasing and reducing the price gap.

1.2 Solar Cell Technology

There are two major types of renewable technologies that utilize solar energy: solar thermal plants and photovoltaic cells. Solar thermal plants utilize the sun’s energy to heat a fluid that drives a turbine to produce electricity. Photovoltaic cells, also known as solar cells, which convert light energy directly into electricity, are the primary focus of this project.

Sunlight carries energy which normally is partly turned into heat when it hits an object. Solar cells are constructed of materials that turn solar energy into electrical current which can be collected for power generation. To increase the voltage of the electricity generated, solar cells can be wired together in series to create larger arrays, known as solar panels. Solar cells accomplish this energy conversion by the use of semiconductor materials.

Semiconductors are the building blocks of solar cells and are materials that do not behave as insulators or conductors, but rather exhibit characteristics that fall in-between. In conductors, the electrons in the outer valence band of each atom are able to move in the solid among nearby atoms, thereby creating an environment within the material for conductive properties to exist. The space between the filled and empty energy bands is known as the band gap. When energy is supplied to the atom and there is no higher energy state for an electron to jump to because the conduction band is so far from the valence band, that material is classified as an insulator since it is a poor conductor. When the band gap is nonexistent or the valence band overlaps with the conduction band, that material is considered to be a conductor. Semiconductors have band gap sizes between insulators and conductors. The theoretical efficiency of a single p-n junction solar cell, known as the Shockley-Queisser limit, is dependent upon the size of the band gap. Silicon has a band gap of 1.1 electron volts (eV). Other materials used for solar cells include gallium arsenide (GaAs) and cadmium telluride (CdTe) which both have band gaps of about 1.4 eV. As seen in Figure 1, the optimal band gap for maximum efficiency is approximately between 1 and 1.4 eV.

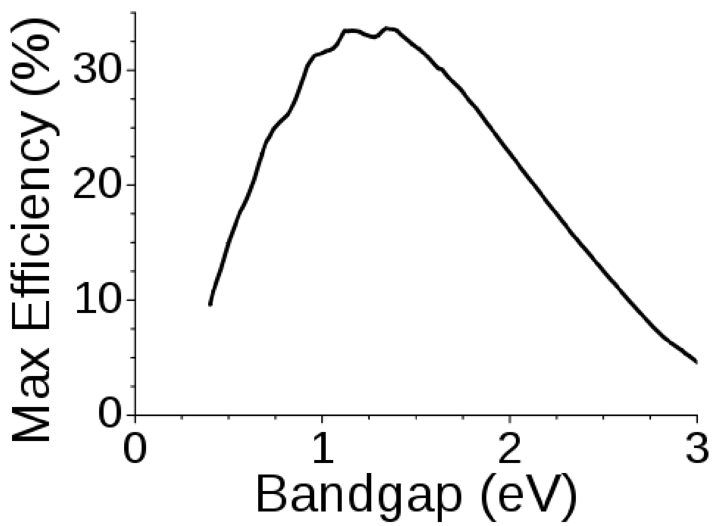

Figure 1 - Shockley-Queisser Limit [1]

Temperature of the solar cells plays a large part in the efficiency. As the solar cell heats up, which is inevitable when in direct sunlight, the band gap of the material will shrink. As the band gap shrinks, the efficiency will decrease as well. It is desirable to have a material that has a band gap on the high end of the optimum range, so that as it heats up, the resulting smaller band gap still falls near the maximum efficiency. Gallium arsenide and cadmium telluride are two such examples.

Silicon solar cells are a popular solar cell category because of availability and cost and will be the technology investigated. These semiconductors are broken down into two types, n-type and p-type. In order to improve its electrical conductivity characteristics, silicon is “doped.” This means that another element is added into the silicon structure to change the nature and number of electrons in the valence shell. Silicon atoms normally have four electrons in their valence shell. N-type silicon typically has phosphorous added to it, which has five electrons in its valence shell. When the phosphorous and silicon combine, one electron is in excess. This last electron is weakly bound and has the ability to move, which improves the electrical conductivity. Alternately, the same methodology applies when creating p-type silicon. In this case, an atom with three electrons in its valence shell is added to silicon. Boron is commonly used for this purpose. The boron-silicon combination creates a “hole” because there are only three electrons versus the normal number of four valence electrons in silicon.

A p-n junction is created when these two types of silicon are placed together. At the interface between the two types of doped silicon a depletion zone forms that creates an electrical field. The depletion zone is a small volume where the n-type free electrons have crossed the boundary to combine with the p-type holes and vice versa. Under equilibrium conditions, the extra electrons from the n-type flow to the p-type and fill the voids that were created in the doping process. This depletion zone acts as a wall between the two sides and prevents any further flow of electrons or holes.

When photons from solar rays are directed on the junction and absorbed by an electron, the increase in energy causes the electron to jump from the valence to the conduction band. For a photon to have this effect on an electron it must carry at minimum the band gap energy, which for silicon is 1.1 eV. As the electrons are forced loose, they migrate from the n-type silicon to the p-type silicon. As the electrons flow, they are prevented from passing back through the depletion zone, producing a voltage potential. Solar cells take advantage of this process by connecting the two types of silicon externally via an electrical load and creating a circuit. The electrons in the p-type layer pass through the circuit and back to the n-type layer creating a current. This process is illustrated in Figure 2.

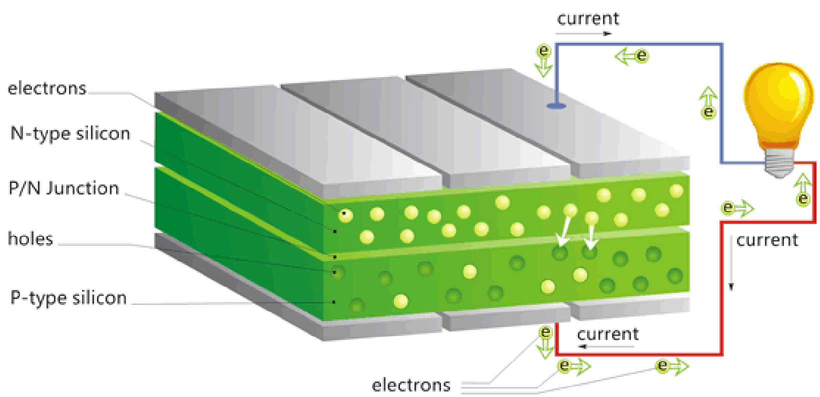

Figure 2 - Solar Cell Circuit [2]

Silicon solar cells are manufactured in several different ways; the three to be examined are monocrystalline, polycrystalline, and thin film, also known as amorphous silicon. Monocrystalline solar cells offer the best efficiencies, but are the most expensive because large single crystals are uncommon naturally and are instead grown in a laboratory environment. Monocrystalline silicon has, as the name implies, an unbroken crystal structure, meaning there are no grain boundaries. Grain boundaries introduce discontinuities that hamper the desired electrical characteristics of the material.

Polycrystalline silicon consists of many small silicon crystals or grains. It is less expensive than monocrystalline silicon, but offers a lower efficiency. Typically crystalline silicon solar cells have a longer lifetime than amorphous silicon cells.

Amorphous silicon solar cells have the lowest efficiency, but are also the least expensive and lightest weight of the three types. Amorphous silicon solar cells are manufactured by laying a thin film of silicon onto another material. Depending upon how the amorphous silicon is manufactured, it can have a band gap between 1.4 and 1.8 eV, which is one reason for its decreased efficiency. Another reason is the method in which it is manufactured inherently creates many grain boundaries and incomplete bonds in the silicon.

1.3 Solar Panels

A solar panel is made up of many solar cells wired together. Depending on the energy required for the specific application, many solar panels can be wired together to create a large array.

Several components are necessary in a system capable of utilizing the energy generated by the solar panel array as shown in Figure 3:

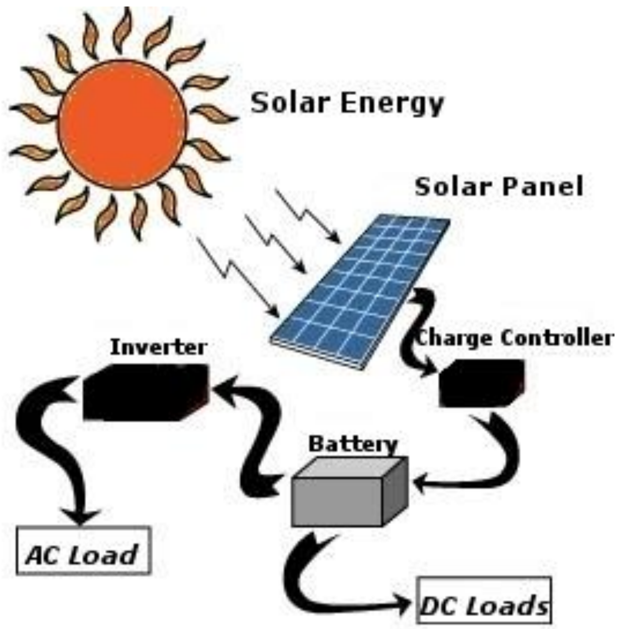

Figure 3 - Typical Solar Energy System [3]

The subject components include a battery, or battery chain, charge controller and inverter. Because solar panels are generally not able to generate energy at night, a battery is needed for storage of the energy that is necessary at nighttime or on cloudy days when the production from the panel is lessened or is nonexistent. Deep cycle batteries are a good choice for this application because they are designed to be discharged to a greater percentage of their capacity. They are also able to deliver lower amperage levels for longer periods of time than other batteries, which is desirable for the consistent loads that would be expected.

The charge controller is also known as a voltage regulator and is included to protect the battery. When the battery is charged to its full capacity, the charge controller prevents the battery from being overcharged, which could decrease its expected lifetime or even cause an explosion.

The last component in this system is the inverter. The inverter takes the charge from the direct current (DC) output and turns it into alternating current (AC), which is the format present in household systems.

2. Methodology

2.1 Approach to Reducing Carbon Emissions from Vehicles

This project provides a conceptual design for the use of solar panels on the roof, hood or trunk of vehicles for the purpose of generating sufficient energy to power auxiliary services and thereby offset the excess carbon emissions generated by these loads. In this case the load to be examined is the onboard air conditioning unit. Running the vehicle's air conditioning unit requires additional electrical energy, which causes the engine to burn more fuel to compensate for the additional load. Figure 4 shows the breakdown of the energy used by an average 27 mile per gallon vehicle.

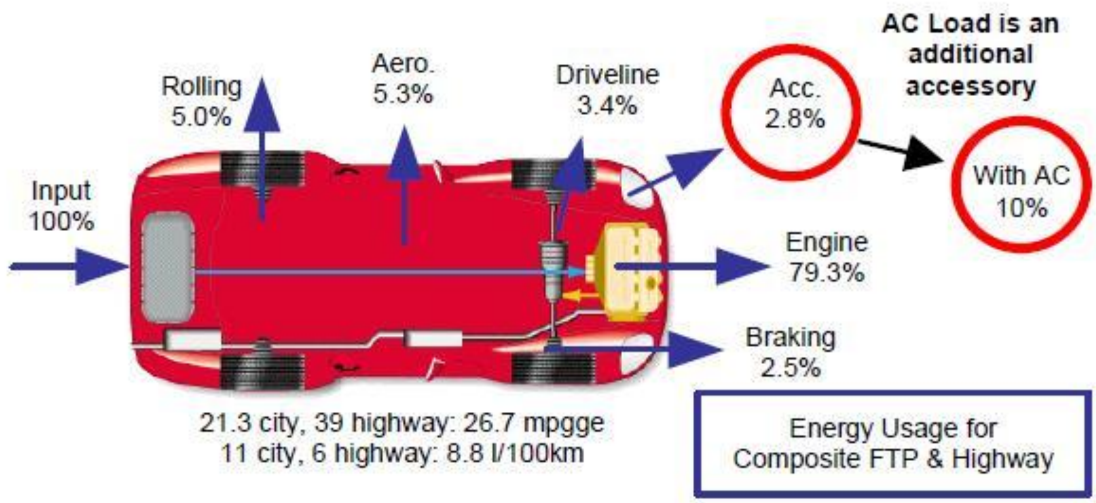

Figure 4 - Energy Usage for an Average 27 mpg Vehicle [4]

The maximum load expected from a vehicle's air conditioner is equal to the energy required to drive the vehicle 35 miles per hour at steady state conditions.[4]

The total amount of fuel that is used to support additional loads due to air conditioning is not trivial. Reference [4], which analyzed usage on a state-by-state basis, estimates that 7.1 billion gallons of fuel are burned annually in the United States for automobile air conditioning. That equates to 69.4 million tons of CO_2 equivalent released into the atmosphere solely as a result of vehicle air conditioning.

Implementation of solar panels would restore that lost fuel efficiency with a "green" technology and represents a fuel savings to the vehicle owner with fewer greenhouse gases introduced into the earth's atmosphere.

To determine the viability of this idea, an analysis must be completed to determine the amount of sunlight that is available at the appropriate locations.

2.2 Solar Irradiance

Different areas of the earth receive different amounts of daily sunlight. These variances are due to the angle of incoming sunlight as a result of the curvature of the earth, orientation of its axis and the path around the sun. As shown in Figure 5, the energy in a given amount of solar radiation is spread over a greater area as the distance from the equator is increased. The latitude that experiences the greatest irradiance varies with the time of year due to the tilt of the earth's axis. The axis of earth's rotation is tilted by about 24° from the plane in which it travels around the sun. This tilted axis causes the four seasons of the year and a changing irradiance, granting larger values for the summer season of June, July, and August in the northern hemisphere and December, January, and February in the southern hemisphere. The irradiance also decreases for the winter season because the tilt of the earth not only reduces the sunlight exposure of a given area, but spreads the energy of the solar radiation over a greater area, thereby reducing the power flux and the amount of energy that can be generated by photovoltaic cells. For instance, the average irradiance in Groton, CT (41.36, -72.02, latitude and longitude respectively) is approximately 480 W/m^2 for the month of June. For the inverse latitude (-41.36, -72.02), which falls in Chile, approximately 1,000 km south of Santiago, the average daily irradiance during the month of June is about 140 W/m^2. During the month of January, the average daily irradiances for these two locations are approximately 170 W/m^2 and 500 W/m^2 respectively.

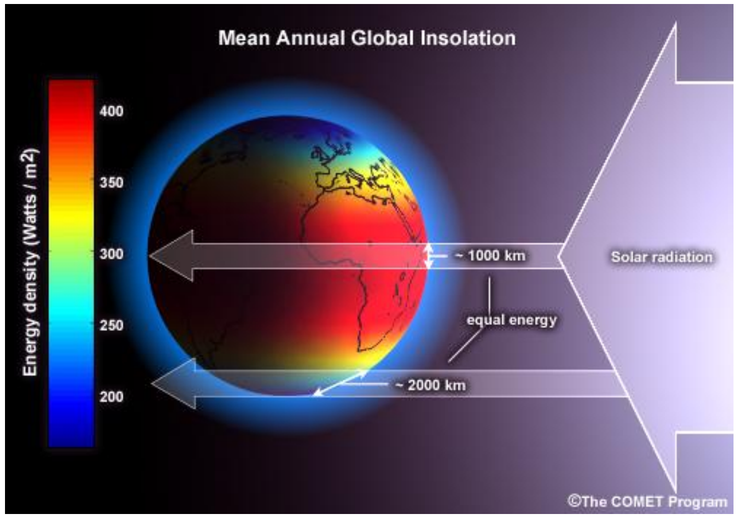

Figure 5 - Average Daily Irradiance (Earth's Tilt Not Shown) [5]

Given a location on earth and time of the year, the irradiance can be defined well. Knowing the irradiance allows the maximum energy that can be generated by a solar panel to be calculated. A comparison of daily irradiance and hours of sunlight is shown for Groton, CT in Figure 6.

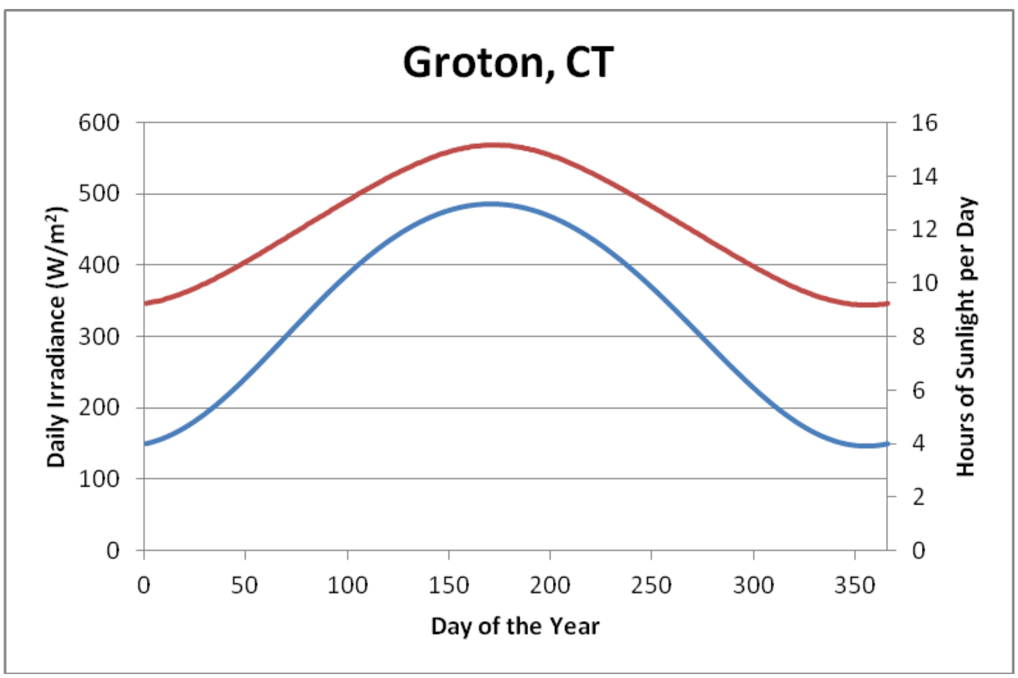

Figure 6 - Irradiance (Blue) and Hours of Sunlight (Red) for Groton, CT [6]

For comparison, the amount of solar irradiation around the United States can be seen in Figure 7.

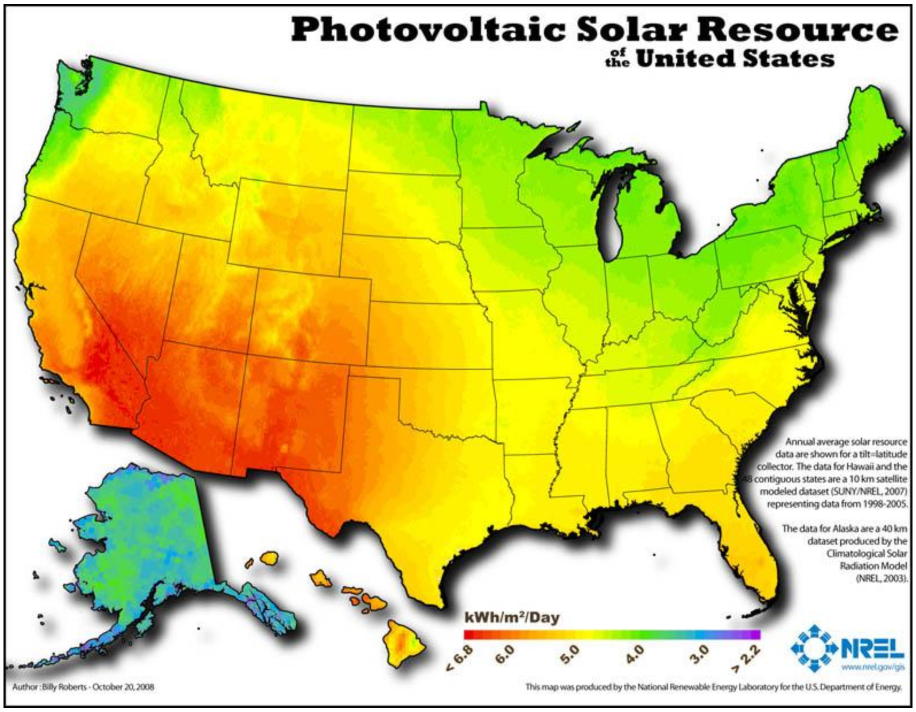

Figure 7 - Average Daily Irradiance in the United States [7]

2.3 Air Conditioning

Air conditioning has become quite prevalent and can be seen just about everywhere. Air conditioning is a closed loop process by which a special fluid absorbs heat from one environment and releases it to another. Air conditioning is also used to remove moisture from the air. Fluids with specific properties are utilized as the working fluids, known as refrigerants. The cycle consists of four stages, evaporation, compression, condensation and expansion. Figure 8 shows the air conditioning cycle.

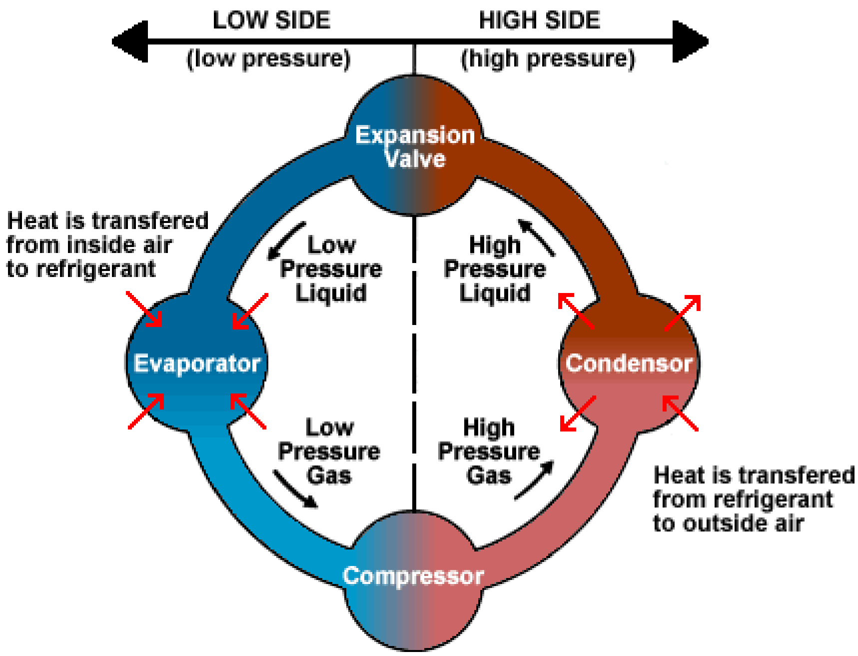

Figure 8 - Air Conditioning Cycle [8]

Using a car as an example, the environment to be cooled would be the cabin and the heat would be transferred to the outside air. Low pressure liquid is exposed to the environment to be cooled via an evaporator or cooling coils. As the refrigerant absorbs heat from the interior environment, it turns to gas. This gas travels to a compressor that increases the pressure and heat via compression. Then, the high pressure, warm refrigerant passes through condensing coils in the outside environment to transfer its heat to the outside air, transitioning into the liquid phase in the process. The final stage is to pass through an expansion valve which lowers the pressure and returns the refrigerant to the beginning of the cycle.

2.4 Energy Requirement

Currently, the additional power required to run the air conditioner comes from the car's battery and alternator, shown in Figure 9.

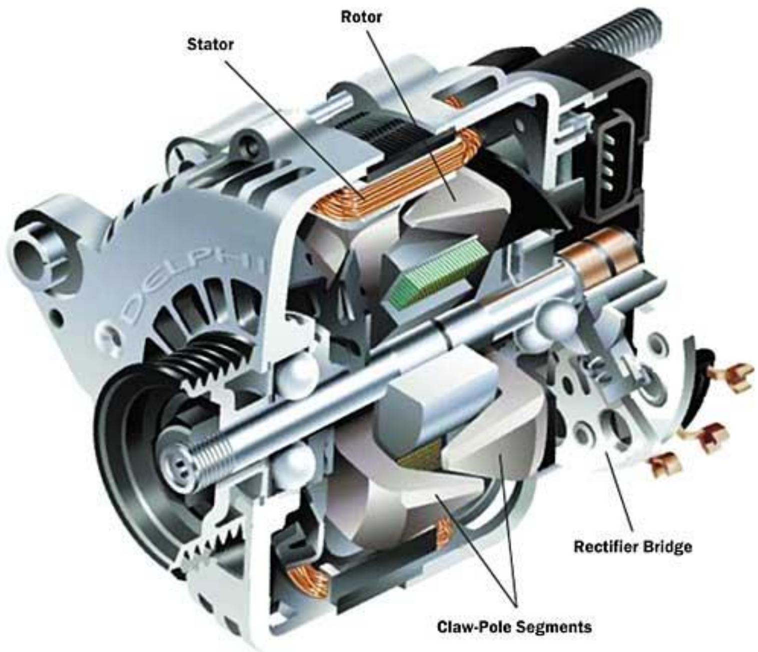

Figure 9 - Automotive Alternator [9]

The alternator is a device that converts mechanical energy into electrical energy. It consists of the following parts: a rotor, stator, diode and voltage regulator. The rotor contains magnets which spin while the stator contains electrical windings that are stationary. As the rotating magnets pass by the stationary electrical winding set, they produce an electrical current. The diode converts electricity from AC to DC which is used to charge the battery. The voltage regulator simply prevents the battery from being charged past its maximum capacity. The alternator is attached via a serpentine belt to the crankshaft, thereby turning the rotor and generating power as the crankshaft turns.

A vehicle's air conditioner requires additional energy based on the loading. The maximum loading can be quite large, varying with the size of the compressor. For the purpose of this project, three different vehicle sizes were studied. As the size of the vehicle increased, so did the size of the air conditioner. A Volkswagen GTI was assumed to have a 3 kilowatt (kW) peak draw, a Jeep Liberty had a 4kW peak draw, and finally a Hummer H1 Alpha was assumed to have a 5kW peak draw from the air conditioner.

2.5 Environmental Impacts

Vehicle emissions contain greenhouse gases, which are defined as those that absorb and emit infrared radiation typically radiated by the earth to space. As gasoline or diesel fuel is burned by a car, many different gases are present in the exhaust stream. The type of gases and the quantity depend on the age of the car and the engine. Gasoline and diesel fuel are hydrocarbons, meaning they are chemically composed of long chains of carbon and hydrogen atoms. As these long chains are broken apart by the combustion process, they recombine into different molecules. The majority of the emissions from vehicles are CO_2 and water vapor. The majority of the nitrogen (N_2), which makes up over three-quarters of air, passes through the engine unchanged. Other gases which are present include carbon monoxide (CO), nitrogen oxides (NO_x), and other volatile organic compounds (VOCs) which mostly consist of evaporated unburned fuel. Catalytic converters are designed to remove these harmful constituents from the exhaust stream; however they are not completely efficient.

For modern vehicles, an average gallon of gasoline will release approximately 8.8 kg of CO_2 whereas each gallon of diesel fuel will release about 10.2 kg. These fuels will also release small amounts of other greenhouse gases as they are burned.

Every greenhouse gas is given a value that corresponds to its impact on global warming. CO_2 is given a value of one and all the other greenhouse gases are indexed to CO_2. This scale is referred to as equivalent CO_2 (CO_2e), or global warming potential (GWP). For instance, air conditioning refrigerant 134a (HFC-134a) has a CO_2e of 1,430, which means that if one kg of HFC-134a is released into the atmosphere, it can have the same global warming impact as 1,430 kg of CO_2. Table 1 lists several common greenhouse gases and their respective GWP.

Table 1 - Common Greenhouses Gases and their Global Warming Potential [10]

Gas	GWP
CO_2	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298
Freon (CFC-12)	10,900
Sulfur Hexafluoride (SF_6)	22,800

CO_2 accounts for the vast majority of greenhouse gases introduced to the atmosphere via vehicle emissions. Other emitted greenhouse gases include CH_4 and N_2O. These two greenhouse gases only make up a small percentage of the emissions and even though they have a higher GWP they also provide minimal impact on the CO_2e.

2.6 Available Area

The three selected vehicles were examined to determine the surface area which could be used to place the solar panels. The roof and hood areas were measured and are shown in Table 2.

Table 2 - Potential Solar Panel Area

	Roof Area (ft^2)	Hood Area (ft^2)	Total Area (ft^2)
GTI	20.2	10.3	30.5
Liberty	22.7	12.4	35.1
H1 Alpha	53.8	24.8	78.6

The H1 Alpha clearly had the largest usable area for solar panels because it has a large roof area. The Volkswagen GTI is a hatchback design which is why it has almost the same size roof as the Jeep Liberty.

2.7 Battery System

A battery system was included in the design so that there would be a constant supply of available energy for the air conditioning. The solar panels are not able to directly supply the power required because the air conditioner draw is greater than the solar panels can supply at peak.

Deep cycle batteries are available in many different voltages and capacities. Care needs to be taken to not discharge the batteries below a certain threshold because their expected lifetime can be reduced if they repeatedly dip below this level. Therefore, when sizing the battery, it should be approximately twice the capacity needed. A 12V battery rated for 833ampere hours (Ah) will supply approximately 10kWh, which is twice the maximum expected for this project.

Discharging the battery quickly decreases the actual usable Ah. This is due to the high internal resistance of the battery and is known as Peukert's Law. If the battery discharge is slowed, the amperage will decrease and will result in more Ah being available from the battery [11].

3. Scenarios and Results

3.1 Gasoline/Diesel Fuel (Baseline)

This scenario will examine the amount of fuel that is used to power the three vehicles previously mentioned if the alternator is the only power source. The average energy density for all grades of gasoline is about 117,000 BTU/gallon [12]. For diesel fuel it is approximately 129,000 BTU/gallon [12]. As the fuels are burned by the engine, the energy is not converted at 100% efficiency; rather a gasoline engine runs at about 35% efficiency while a diesel engine runs slightly higher at around 40%. This results in a usable energy of only 41,000 BTU/gallon from the gasoline engine and 51,600 BTU/gallon from the diesel engine. Losses are also experienced in the alternator as the energy is transformed into electrical energy. Assuming an operating efficiency of 55% for the alternators in both gasoline and diesel engines, only 22,500 BTU (6.6 kWh) of electrical energy is extracted from each gallon of gasoline and 28,400 BTU (8.3 kWh) per gallon of diesel fuel. Only 19.3% of the energy contained in one gallon of gasoline is converted into electrical energy. For diesel fuel the efficiency is slightly better at 22%.

If the air conditioner is used for one hour, that equates to 0.45 gallons of gasoline for the Volkswagen GTI (3kW) , 0.6 gallons of gasoline for the Jeep Liberty (4 kW), and 0.6 gallons of diesel fuel for the H1 Alpha (5kW). If used for one hour every day for the months of June, July, August and September, this totals 55.4, 73.9 and 73.3 gallons of fuel for each vehicle respectively.

The emissions for CO_2 are dependent on the volume of fuel burned; however, for the other two greenhouse gases investigated, CH_4 and N_2O, the quantity released to the atmosphere is a function of the miles traveled by the vehicle. For modern vehicles, specifically gasoline passenger cars, 0.0173 grams of CH_4 and 0.0036 grams of N_2O are released per mile [13]. For sport utility vehicles (SUVs) the numbers are 0.0163 grams of CH_4 and 0.0066 grams of N_2O. Finally, the H1 Alpha, which is classified as a diesel heavy-duty truck, emits 0.0051 grams of CH_4 and 0.0048 grams of N_2O is released per mile driven.

3.2 Standalone Solar Power System

In this scenario, solar panels are the only source of energy for the air conditioner and do not receive additional energy from a plug-in system or the alternator. First, the types of panel must be selected, monocrystalline, polycrystalline, or thin film. The efficiencies of each vary so one value was assumed to be constant for each. Monocrystalline was 20%, polycrystalline was 15% and thin film was 12.5%.

The air conditioning was assumed to be used for the same four months as the baseline scenario. The average solar irradiance in Groton, CT during these four months is 383.26 W/m^2.[6] Combining this value with the efficiencies stated previously, monocrystalline solar panels are able to produce 76.65 W/m^2. Polycrystalline and thin film solar panels are able to produce 57.49 and 47.9 W/m^2 respectively.

Next, these specific values will be combined with the roof and hood areas of the three vehicles from Table 2 to determine how much power can be generated from the available areas. Table 3 below shows the results.

Table 3 – Potential Power Generation in Watts for Each Solar Panel Technology and Vehicle Investigated

	Potential Power Generation (W)		
	GTI	**Liberty**	**H1 Alpha**
Monocrystalline	217.3	250.0	559.6
Polycrystalline	162.9	187.5	419.7
Thin Film	135.8	156.3	349.7

Comparing these values to the required energy from the air conditioners for each vehicle, the required period of exposure time for each vehicle and solar panel technology can be computed, as seen in Table 4.

Table 4 – Required Daily Exposure Time for Each Solar Panel Technology and Vehicle Investigated to Meet Air Conditioning Values

	Required Exposure Time Per Day (Hours)		
	GTI	**Liberty**	**H1 Alpha**
Monocrystalline	13.8	16.0	8.9
Polycrystalline	18.4	21.3	11.9
Thin Film	22.1	25.6	14.3

From Table 4 it can be seen that the required exposure time is large and in one case (Liberty/thin film) requires more hours than there are in one day. The average amount of daily sunlight in Groton, CT for June, July, August and September is slightly over 14 hours. Taking that into consideration, only three of the nine cases are feasible. The monocrystalline and polycrystalline scenarios for the H1 Alpha and the monocrystalline for the GTI are the only cases under 14 hours.

Even though it is possible for these three cases to work, it is unlikely on an average day that the panels would be exposed to the necessary amount of sunlight because of clouds or shade. Therefore, an additional source of energy is likely to be required, or else the vehicle occupants may suddenly find themselves without air conditioning on a warm day.

3.3 Stationary Solar Panel Support System

In this scenario, the solar panels receive additional energy from a plug-in system. Infrastructure could be created at residences or travel destinations where a canopy could be used to both shade the vehicles underneath and provide solar panels on the roof of the canopy to charge the onboard battery, as seen in Figure 10. This option provides much more solar panel area and therefore more energy for the onboard system.

Figure 10 – Example of a Solar Canopy [13]

The area of the average parking space is almost 10 m^2. If a canopy system was utilized and the roof covered in solar panels, energy could be generated while the car is parked at home or the occupants are at work. Table 5 shows the sunlight exposure time required for each vehicle's air conditioner for a nearly 10 m^2 solar panel area.

Table 5 – Required Exposure Time in Hours to Meet Air Conditioning Needs for a 10 m^2 Solar Panel Area

	GTI	Liberty	H1 Alpha
Monocrystalline	4.1	5.4	6.8
Polycrystalline	5.4	7.2	9.0
Thin Film	6.5	8.6	10.8

As expected these values are more acceptable than the first scenario (Standalone Solar Power System) since the area has increased. All nine cases fall within the average amount of daily sunlight by at least three hours.

If implemented in places beyond the owner's residence, this scenario requires construction of a large infrastructure requiring the cooperation of many businesses and industries. The vehicle air conditioning benefits are dependent upon the implementation of these devices by their workplace or travel destination so as to support the solar energy needed for the vehicle design.

3.4 Fuel Supplemented System

In this scenario, the solar panels are once again mounted on the roof of the vehicle. However, an alternator is also installed and is available to supply additional energy if required. The main source of energy is still the solar panels, but whenever the battery has insufficient energy to power the air conditioner or clouds/shade prevent adequate sunlight from reaching the solar panels, the alternator can produce additional energy to keep the air conditioner running.

This final scenario provides the greatest flexibility to vehicle owners, because they still have the option to use the air conditioner even when the other scenarios, which rely solely on solar energy, would prevent it. This option does offset the majority of the greenhouse gases that would have been produced because the solar panels will provide most of the energy required to run the air conditioner.

4. Conclusion

Based on the evaluations completed of the three scenarios, the option that offers the greatest flexibility is the third, which locates solar panels on the roof and trunk of the vehicle, but also includes a conventional alternator as a backup supply. Inevitably at some point the weather will prevent the solar panels from gathering energy to use for the air conditioning. However, the solar panels will provide a source of energy, which will lessen the amount of fuel burned and reduce the output of greenhouse gases to the environment.

The amount of solar energy available in Groton, CT is lower than over most of the United States. So other areas, such as the Southwest may be able to support a solar-only system and completely forgo the alternator backup. Also, as the technology improves, the efficiencies of solar panels will increase and therefore have the ability to convert more solar energy into electrical energy.

5. References

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6. Appendix A: Vehicles Investigated

Volkswagen GTI [17]

Jeep Liberty [18]

Hummer H1 Alpha [19]