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作品名稱	A 100% Solar Electric Vehicle: Applying high efficiency solar modules in sustainable transport
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Abstract

As our planet suffers the effects of climate change, it is only a matter of time before society will have to centre all aspects of development around sustainability. In the past, clean solutions for transportation have been dismissed due to the higher cost, and lower efficiency than fossil fuels. However, in the past few decades, there has been a steep decline in solar module cost, and and a steady climb towards higher efficiency. From my findings in this project, I have concluded that we are now at a point where we can embrace the clean, renewable potential which our sun offers.

I have created and tested a proof-of concept electric vehicle (Solar EV), which can run indefinitely during daylight hours, provided sunny conditions. There are several mechanical features of my project which highlight the potential that renewable energy in transportation can have. Firstly the vehicle's 500W motor is powered by 3 100W solar modules, and 3 50W modules, for a total of 450W or power generation. This means that when driving at anything less than 90% throttle, the Solar EV can run continuously without needing to stop to charge or refuel.

Another design mechanism installed in the vehicle are three 12V lead acid batteries. These batteries allow the Solar EV to be powered for over 1.5 hours, which is useful during cloudy conditions, night, and most importantly, when driving through areas of shade. A unique efficiency component designed into my vehicle is the linear actuator I installed into the module racking system. This design element allows the tilt of the modules to be altered, to maximize the efficiency of the solar module array. At early or late hours of the day, it can be heavily tilted with the press toggle switch, or kept at a relatively flat level when the sun is the highest in the sky. I ran a series of trials to figure out whether or not the theoretical data matches up with the experimental results. After my series of trials, the bike was yet to run out of power. The solar vehicle reaches speeds up to 32 km/h, however comfortably glides at around 25 km/h. The linear actuator I installed allows the solar modules' tilt to change . During different times of day or year, the sun is at different heights in the sky, however it is very important to maximize the solar potential. With the press of a switch, the module can be actuated to account for this.
Lastly, regenerative braking captures the energy from braking. Using the reversible nature of a DC motor with a specialized motor controller responding to feedback from the brake actuators allows the vehicle to reuse energy that would otherwise be wasted as heat.

An experiment was performed after completion as a way to understand what the optimal speed to ride the Solar EV would be. This experiment was performed to test the relationship between motor power output and velocity for the Solar EV, which will allow us to figure out the most efficient travel speed. The diminishing velocity returns seen in the experiment show that small reductions in velocity can translate into large savings in transportation energy requirements. The same concept can be applied to sustainable transport in boats and trains, where it is seen that an increase by several km/h can have an immense impact on the power demand. The difference between a boat travelling at 25 knots as opposed to 26 knots does not significantly affect the time it takes to reach the destination, however it could allow for the significant reduction in the amount of energy required.

The potential seen in my Solar EV also raises inquiries on the utility of solar modules in other areas of transport. Transport ships and trains are two examples of vehicles that have large amounts of exposed surface, and high carbon and other emissions. My project not only demonstrates how solar technology can be used on a Solar EV, but opens the door to the immense potential utility on other vehicles.

Introduction

For a long time, solar photovoltaic energy generation has been seen as inefficient for the space it requires, as well as too expensive to be competitive with fossil fuels. The combination of high cost and large solar module area per Watt limited the utility of solar photovoltaics.

However, the prices of solar modules has decreased exponentially in the past few decades. Meanwhile, the commercial efficiency of solar panels has also gone from around 8% in the 1970's to exceeding 23% today. The transportation sector accounts for around one-quarter of global carbon emissions. Since the industrial revolution, and the invention of internal combustion engines, burning fossil fuels in transportation has been the cheapest and most efficient energy source for ground and marine transportation.

Attempts at cleaner solutions have been made over the decades, but only in the past few years have renewables become economically viable contenders in transportation.

The Solar Electric Vehicle (Solar EV) used in this experiment has been designed, and constructed in order to demonstrate and test the potential of modern, standard commercial efficiency solar panels in a basic transportation application. Once completed, the Solar EV was used in a series of trials, designed to test the relationship between power and velocity. This data was then analysed and applied to the broader potential freight transportation uses in shipping and rail. The Solar EV has the following design capabilities:

- **Can run indefinitely during sunny, daylight hours**. Three 100W solar panels, and three 50W solar panels were used to supply the 500W motor with 450W. This is enough energy to travel without pulling over to recharge, or re-fuel (when travelling at almost full-throttle).

- **Travels at a velocity around 25-30 km/h**. The 500W motor powers the Solar EV to reach velocities over 30km/h, but to comfortably glide at 25 km/h, due to the weight of the panels, seat, and driver.

- **At full charge, can also run for 1 ½ hours without sun**. Three lead-acid batteries have been installed so the vehicle can travel even when it is not sunny. This allows for travel either at night, during rainy or cloudy times of day, and most importantly, when travelling through patches of shade:
  Electric motor (DC) = 500W (Maximum legal allowance)
  = 36V
  A = W/V
  A = 500W / 36V
  A = 13.9

Batteries: 12V, 22 Amp hours, 264 Wh
= 1.58 hours of charge without sunlight

- **Linear actuator allows for the tilt of the solar panels to be easily adjusted during operation of the vehicle**. As the direction of the Solar EV, or the sun's placement in the sky changes, the linear actuator allows the vehicle to track the sun, in order to operate at maximum efficiency.

- **Regenerative braking** captures the energy from braking. Using the reversible nature of a DC motor with a specialized motor controller responding to feedback from the brake actuators, allows the vehicle to re-use energy that would otherwise be wasted as heat.

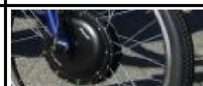
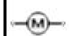
Voltage Source (PV Module)		
Battery (12 V Lead/Acid, 22Ah)		
Solar Charge Controller		
Diode		
DC Hub Motor (36 V 500 W)		
Voltmeter (Solar Charge Controller Display)		
Ammeter (Motor Control Unit Display)		

Figure 1: Table of Electrical Symbols

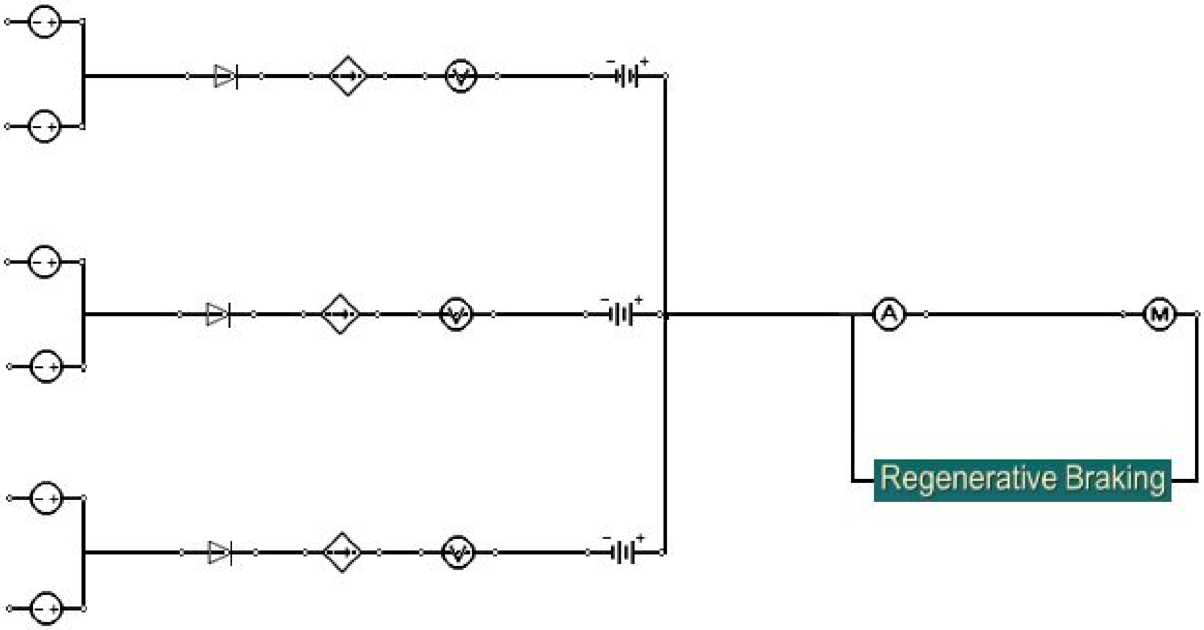


Figure 2: Electrical Diagram of the Solar EV

The Experiment:

Purpose

This experiment was performed to test the relationship between motor power output and velocity for the Solar EV, which will allow us to figure out the most efficient travel speed.

Hypothesis

As the power output (watts) increase, the velocity of the Solar EV will increase. Because this is a real world field experiment, various elements of friction, predominantly wind resistance, will result in a non-linear increase.

Materials

- Solar EV
- Time
- Ammeter (to measure watts)
- Measuring tape (100m)

Independent Variables

The independent variable in this experiment is the power (in watts) applied to the Solar EV. Wattage between 0W (no power) and 500W (the maximum power) are measured.

Dependent Variables

The dependent variable in this experiment is the velocity (in kilometers per hour). The velocity of the Solar EV at each power increment displays the range in which power can be conserved and velocity can be maximized.

Procedure

1. Measure 100m on a flat, paved surface.
2. Label markings on throttle to indicate 100W, 200W, 300W, 400W, and 500W.
3. Actuate solar panels to face the sun.
4. Begin timer while simultaneously turning to full throttle.
5. Observe the highest speed reached.
6. End timer and release throttle after 100m dash.
7. Record results (Watts and Power).
8. Repeat steps 3-7 starting at 500W, decreasing by 50W each trial.

Figure 3: Solar EV during experiment trials

Data Collection

Table of Power vs. Velocity of the Solar EV

Power (Watts)	Velocity (km/h)
0	0
54	11
87	12.9
102	14.4
144	16.0
176	17.5
208	18.9
250	19/6
299	21.1
345	22.0
370	23.7
407	23.6
424	24.0
460	24.2
500	24.3

Data collected from the series of trials comparing the relationship between power and velocity.

Data Collection

Power vs. Velocity of the Solar EV

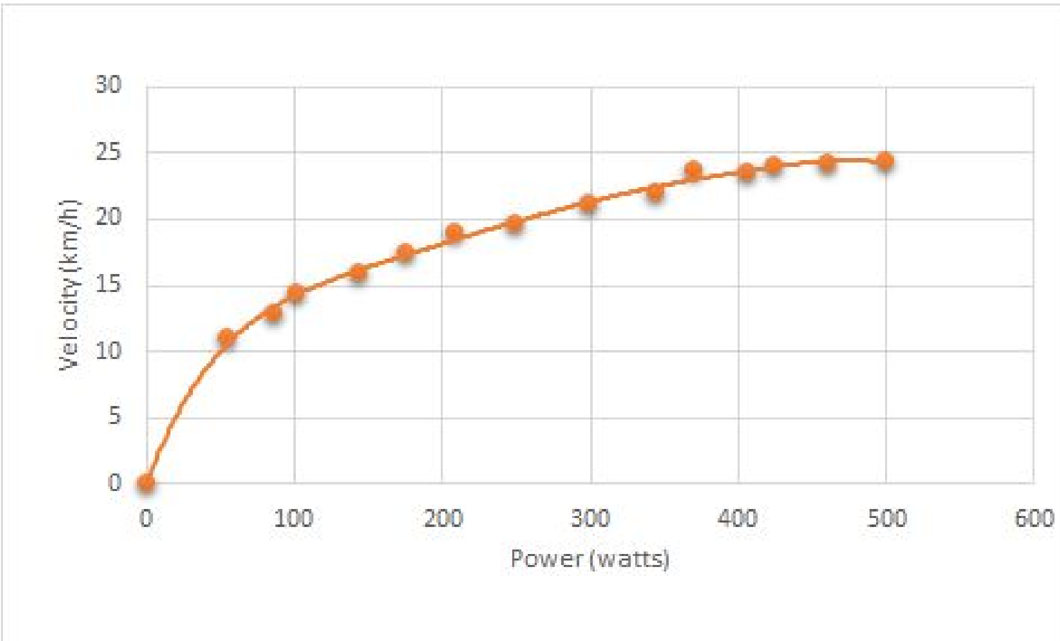


FIgure 4: In this graph, it is observed that the amount of powered applied to the Solar EV did not form a linear trend. At around 400W, there appears to be very little increase in the velocity, as the bike did not reach over 20 km/hour in the 100m stretch.

Discussion

The Importance of Sustainability

The devastating effects that climate change has already had on our planet demonstrates why there is a need for change. Both our oceans and our land are in desperate need for sustainability Our oceans are the planet's largest single mechanism for removing excessive carbon dioxide from our atmosphere. They absorb more carbon dioxide than all of terrestrial plants on Earth. Unfortunately, there are limits to the oceans, as well. As our oceans become saturated with attenuated carbon dioxide, the equilibrium concentration of carbonic acid increases, which has some negative effects to the ecological world.

Ocean acidification is the decrease in the ocean water's pH. This occurs when carbon dioxide is absorbed into the ocean. When carbon dioxide and water contact, a chemical reaction occurs. H^+ ions break apart from the carbonic acid, which lowers the ocean's pH. In some parts of the world, the sea's pH has already decreased by more than 0.1. Whenever there is a great shift or disturbance in an ecosystem. it is well- known that this leads to the destruction of sea life, and coral reefs.

There is serious damage being done on land, as well, which is more easily observed by humans. Desertification has been spreading all across dryer parts the world, turning plentiful land into lifeless, arid stretches. In Africa, 650 000 km^2 of agricultural land has been lost in the past five decades. Meanwhile, an additional 6000 square kilometers of land have been incorporated into the Sahara desert since 1990. The Sahel region of Africa is one of the areas at the highest risk, and is home to around 100 million people, who are all at risk for having their entire food source desertified. The worst part is the fact that these people are not the main contributors to climate change, but are the most heavily impacted by it, and have no means of preventing it from happening.

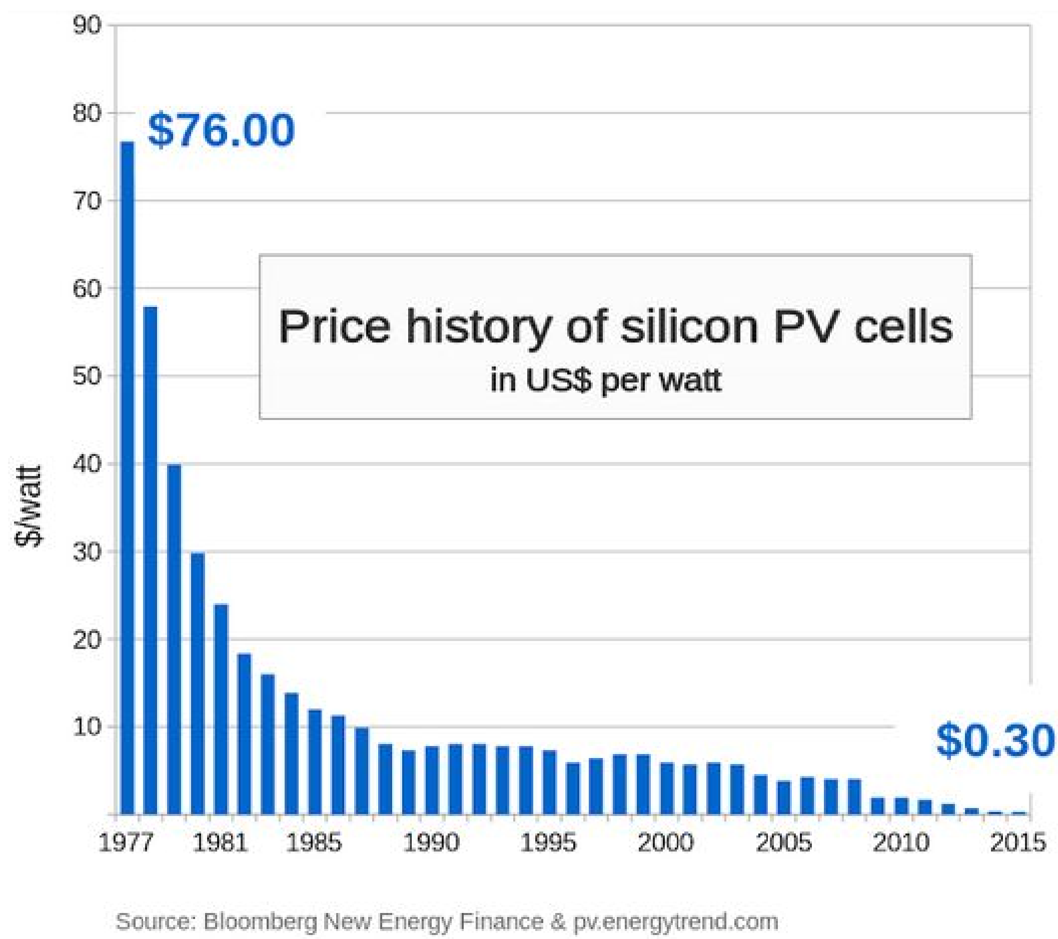
Other parts of the world, such as in the southern United States, Central Asia, Australia, and much of South America, are vulnerable to desertification as well, if they haven't been affected already. Essentially, the entire world is at risk of being impacted by this phenomenon, either directly, or indirectly.

When desertification affects a region, the area loses fertile land, bodies of water, and much of the flora and fauna. Soil degradation occurs, and prevents crops from firmly planting roots. This, of course, creates a major problem for agricultural land. It is estimated that 2 billion people live in drylands, and 90% of these people live in undeveloped countries. As Climate Change, and over-exploitation become more noticeable, where will this 30% of the world go? The answer is not to run away from our problems, but to use our scientific understanding to solve it.

Why Now?

There have been two key aspects behind the very pronounced gains in the economic utility of solar PV in recent years:

1. **PV Module Prices** - Slow but steady manufacturing improvements over the last 3 decades allowed for a significant technological change in the way that PV wafers were made in 2008. This was then compounded by massive global investment in module manufacturing capacity. These economies of scale have has had a very pronounced impact on the cost of solar PV modules.



Graph displaying the cost of Solar PV from 1977 to 2015

2. **Solar Module Efficiency Improvements** - The potential of solar power has been apparent for a long time.

"I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that."

Thomas Edison

Solar Module Efficiency is simply the percentage of the light energy hitting a solar cell that is transformed into electric current. For example: 100 Watts of light energy hitting a solar cell resulting in 10 Watts of electricity being generated represents a 10% Efficient solar cell. The continuous work of thousands of scientists and technicians have contributed to the steady upward trend in solar cell efficiency.

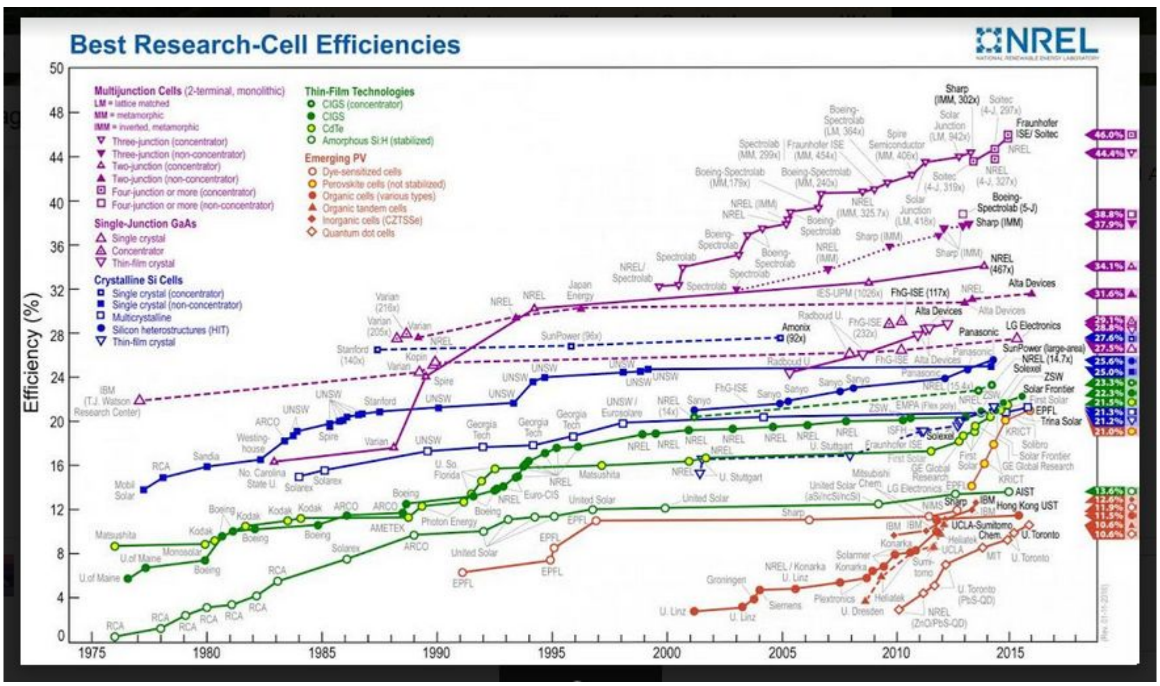


FIgure 6: Graph of the efficiency of different types of solar module from 1975 to 2015

The compounding trends of these 2 variables (Module Prices + Efficiency Improvements) offer an extreme opportunity, at a time when climate change concerns need it the most. Just as importantly, both of these trends are continuing today. This means that the technologies built on these trends offer increasing environmental and commercial potential every day. As with all emerging sustainable technologies, innovative engineering solutions are mandatory in order to overcome the remaining implementation barriers. To execute the application, and test the utility of a mobile solar PV power plant in transportation, a simple terrestrial vehicle was a reasonable first step.

Applications in Transportation:

Freight Trains: Trains are an example of a mode of transportation which usually travels across relatively flat ground, and has a large surface area. Hence, it stood out as being a possible area on which to mount solar panels. Box car roofs are an ideal mounting location for solar modules. Trains without roofs can be modified with solar module roofs. Roofless cars can sometimes release chemicals from their cargo, which is harmful to the environment, providing greater benefits to this retrofit.

The electrical conductors needed to connect solar roof rail cars can be easily installed into the current coupling system, as air brake lines are already connected between each railcar on each train.

Since a longer train requires more power, the solar roof power generation capacity automatically scales up with larger trains.

Additionally, the engines of most trains are currently diesel-electric, meaning there are already electric DC motors in place. This could be easily retrofitted to connect to the rooftop solar on trains directly to the DC electric drive motors. The limited modification would allow a train to operate normally, burning diesel, when additional power was needed, or during the night, or extensive clouds.

The calculations for how much power would be generated is shown below:

Average train engine output = 3 000 horsepower
= 2 200 kW
= 2 200 000 W
Average train car area = 17 m x 3.2 m
= 54.4 m^2
Solar panel = 100W/ 0.5m^2
= 10 880W/ train car

An average train has around 120 cars. Hence, if the entire surface area of a train were to be covered by solar panels, the train could seek 60% of its peak diesel engine energy output from these solar panels. However, at normal lower horsepower travel, or for different sized trains, this number could fluctuate to significantly higher numbers.

Cargo Ships: Shipping is another area where there are vast deck areas which could be transformed into a solar field. Large cargo vessels spend days or weeks over the ocean, where there is nothing to produce shade, and comparatively lower cloud cover than on land. Additionally, similar to freight trains, there are DC electric motors on board many vessels already, meaning it would be relatively easy to install the panels on preexisting freighters. Better yet, designing a solar freight ship could lever these existing marine transport elements, while optimizing hull/deck design to incorporate solar generation.

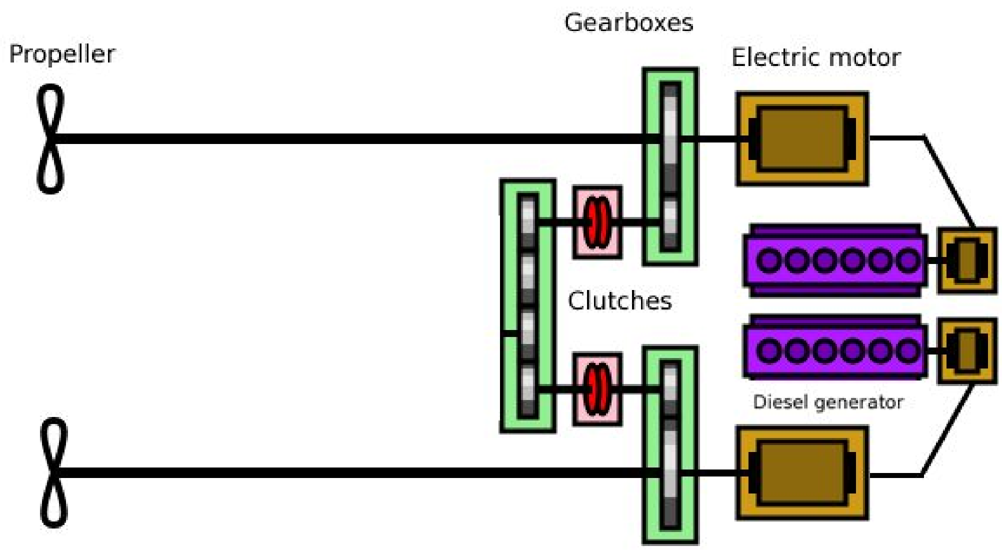


Figure 7: Diagram of a diesel generator used in many areas of transportation

As an example calculation, here is the common TI-class supertanker:

Area of a Cargo Vessel = 380 m x 68 m
(TI-class supertanker) = 25 840 m^2
= (25 840 m^2/ 0.5m^2) x 100W
= **5 168 000 W** would be produced by surfacing the TI-class supertanker vessel in solar panels.

Cargo Vessel Propulsion = 32,000 hp
(TI-class supertanker) = 23 862 396 W
= 22%

Upgrades to Current Vessels or Future Vessels:

- Deck covered in solar panels.
- Linear actuators operating retractable solar array wings. This adaptation would allow for twice the power to be produced, as well as the ability to tilt towards the direction of the sun.
- Larger beam to length ratio, and larger deck area design, less pronounced, but similar to aircraft carriers. (decreases hydrodynamic efficiency qualities, offset by substantial increases the surface area for greater solar generation potential).

Starting with 22% of daytime operation fuel savings, for current vessel retrofits, design elements can be implemented to optimize deck space in new vessels to reach an estimated 40% of daytime operation. Retractable solar array wings can offer an additional, compounded increase toward 80% of daytime operation.

These projections are based on the modules that were used in the Solar EV. With module efficiency gains, and higher efficiency modules already available, these numbers will only increase from here.

In shipping, slightly lower velocities also confer tageable benefits:

- Wake is reduced from ships, which reduced coastline erosion and impacts on people.
- Whale strikes have been proven to be reduced when speeds are reduced.
- Shipping safety slower speeds reduce collisions and groundings.

Advantages of Application to Transportation

1. **Emission Reduction** - The greatest advantage to using renewable energy in transportation is the reduction of Carbon emissions. Over a billion tonnes of Carbon dioxide were produced last year from the shipping, which accounts for around 5% of global emissions. As climate change continues to impact the environment, it is only a matter of time before all aspects of society will be retrofitted to prepare for, and mainly to prevent climate change. The cost of designing transport to accommodate solar efficiency is not comparable to the effects sea levels rising, mass extinction, and natural disasters will have on civilization.

2. **Reduced Operating Costs** - Diesel generators with electric motors is the standard in ships and trains. Converting to solar energy would not use the diesel generator, but would utilise the pre-existing electric motor, which would allow for savings in operating costs on a per kilowatt basis.

3. **Fuel Cost Savings** - When it comes to enforcing change among corporations, it ultimately comes down to economic efficiency. One common concern with solar power is the cost of construction. However when the constant cost of the millions of tonnes of fuel is compared to the fixed cost of solar modules, it is hardly a concern. For cargo ships, spending thousands of dollars per hour on fuel is regular. This means that the millions of dollars spent on installing solar modules (which last decades) is a significantly better economic investment than the millions of dollars spent on fuel per month.

Conclusion

The importance of these findings centers on the utility of transport velocity as a variable that can be manipulated at our discretion. The diminishing velocity returns seen in the experiment show that small reductions in velocity can translate into large savings in transportation energy requirements. The same concept can be applied to sustainable transport in boats and trains, where it is seen that an increase by several km/h can have an immense impact on the power demand. The difference between a boat travelling at 25 knots as opposed to 26 knots does not significantly affect the time it takes to reach the destination, however it could allow for the significant reduction in the amount of energy required. Since sustainable energy sources, such as the sunshine that our solar vehicle relies on, are not always homogeneous (like fossil fuels), allowing velocity to enter the optimization equation introduces extensive flexibility, and utility gains.

Designing ship and train transportation systems to operate moderately slower when/where required, compounded by continued module price reductions and module efficiency increases, offer strong optimization synergies, with 2 of the 3 variables increasing continually in our favour, over time.

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This is a workable idea that can be spread easily to the public. The research is done in a comprehensive way in terms of energy, environmental and mechanical engineering fields of study.The result of a 100% solar electric vehide turns out to be attractive for someone who wants to live more environmental friendly.