SOLAR VEHICLES AND ROADS

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1. INTRODUCTION

Although the direct conversion of solar energy into electric, the so-called «photovoltaic effect», was noticed almost two centuries ago, it's in the recent years that the photovoltaic conversion of solar energy has become the primary branch of solar devices industry because of its numerous technological advantages. Solar energy can produce 1700 kWh/m^2 of electrical energy on average day (in Europe about 1000 kWh/m^2, in the Middle East about 1800 kWh/m^2, in Africa even more). In Serbia, that value is about 1400 kWh/m^2. The solar energy application can be performed in two ways: by converting solar energy into heating energy and by converting the solar radiation into electrical energy, which can be applied in almost all spheres of social life.

The standard components of photovoltaic systems are the FN modules-panels, controllers and battery charging regulators, accumulators or batteries, cables and mounting systems, as well as the convertors of direct current into the alternating current – the inverters (autonomous and network). The direct current produced in the solar cell is taken to the controller by cable which prevents the excessive battery charging, but it also has other roles, depending on the specific applications. The application in traffic is becoming more important since radical changes are expected in the traffic managing systems on the roads through an active communication «with the roads» by applying virtual systems. In this paper, the technical elements of solar vehicles and roads were displayed, their intercommunication and ways of developing.

The growing popularity of this type of energy, the solar panels production will cause their price reduction, so it is realistic to expect its mass application with vehicles in the near future. Momentarily, the FN module prices are €2,5 – €3,5/W and the complete systems are installed at €4-6/W and, depending on the system type and power, the prices of panels are about €300 per vehicle [4]. Panels can produce the power between 750 kWh and 1500 kWh a year, per installed kW, which creates the solar electricity price from 20 eurocents/kWh to 40 eurocents/kWh.

2. SOLAR VEHICLES

Numerous researches are directed to solar vehicles designing, to material and equipment such vehicles should possess. From testing and verification of characteristics to the mass production there are only a few the requests which, together with normative regulations, make this vehicle application very complex. The basic structure of a solar vehicle is: the chassis, the body shape and material, the battery, the engine, the electronics,

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the solar panels, the total vehicle dimensions, the number and arrangement of operating wheels etc.

Most solar vehicles should use the tube-frame chassis as a truss or a one-piece chassis made of composite materials, figure 1.

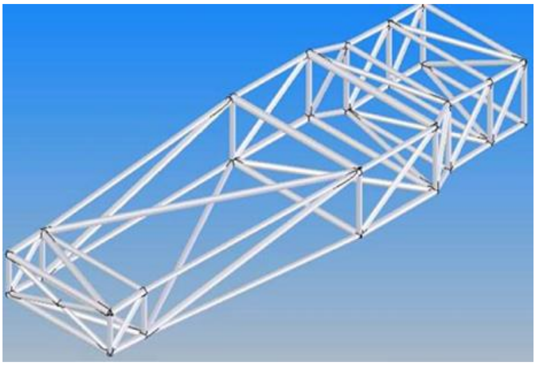

Figure 1 Chassis shapes

The tube-frame chassis is generally cheaper and easier to be designed than the one-piece composite chassis. On the other hand, the one-piece chassis is of lighter mass than the tube- frame one and it enables us to disassemble the vehicles easily into components so the mechanical and the electrical subsystems could be separated. The vehicle mass influences directly on the rolling resistance, on lateral forces in road bends so the smaller the vehicle mass is, the less kinetic energy it needs, which enables the improvement of other characteristics. Vehicle mass isn't equally important for the aerodynamics, the kinetic energy needed or the chassis construction since it has different effects on some vehicle performances.

The vehicle's exterior is also very important when designing a vehicle because of the aerodynamic air resistance which appear at considerable speeds should be reduced. This aerodynamic resistance directly results from the vehicle's shape (the front part of the vehicle is especially important), and it influences the vehicle as the normal projection of force in relation to the air flow direction. Because of this, solar vehicles generally have very low profiles and are completely closed.

Besides the obvious aerodynamic advantages, the vehicle exterior supplies support for the solar modules which are usually placed on the roof of the vehicles. A typical solar module has the power of 80 W to 100 W and the voltage of 12 V. Its dimensions are 100 cm – 50 cm. Although there is a great number of photovoltaic materials, most often the solar (photovoltaic) cells are, as semiconducting structures, made of amorphous silicium (Si) or of gallium -arsenide compounds (GaAs) or some other materials (CIS, CdTe, InP). There have been many investments in the development of silicium heterocell (SANYO solar cell) lately. Silicone (Si) cells parts represent a great majority of all solar modules, and, consequently, they are the cheapest solution. However, even the most efficient Si cells can reach only 20% of energetic efficiency, while the GaAs cells own the possibility and efficiency of 40%.

On the other hand, the GaAs cells production is much more expensive and that's why they are presently used only in space applications. However, the Si cells have their advantages over the GaAs cells (except for their price) because they proved to be more efficient in the conditions of bad light or of the low wavelengths spectrum.

By connecting more photovoltaic cells, a photovoltaic module is produced, with common operating unidirectional voltages of 12 or 24 V, the power of which depends on the total area of all the cells. The unidirectional voltage of the photovoltaic module is changeable and, to control it precisely, it is conducted into the voltage reducer. The battery is charged by a regulated voltage or the unidirectional (DC) consumers are supplied. Voltage from the battery goes into the inverter (a device which turns the DC into the alternating current (AC), and the unidirectional voltage of 12 v into an alternating of 220V) so the alternating consumers (DC) could be supplied. The portable modular chargers can be connected (attached) to a classical electric energy source (in special stations for charging, garages, SSG or landings by the road) when the vehicle is not moving or during the drive for maintaining the battery current level (1A to 2A) through the so-called «super-fast chargers». Batteries can also be charged by solar energy via solar cells placed on the roof of the vehicle. The degree of solar cells usage is 16% and they can Ni-Cd batteries completely in five days at constantly good weather.

Although the subsystem for energy (battery) storage isn't indispensable in solar vehicles, it is recommended that it should be so there wouldn't come to the decline of vehicle performances in the bad light conditions or in the surroundings which aren't ideal for solar vehicles, considering that the power needed for the drive varies depending on the vehicle's speed, wind strength, state of roadways etc. An efficient battery or other systems for energy storage management can considerably minimize the influences on vehicle's performance, the influences which resulted from some of the variations mentioned. The capacity of this storage system varies and it is directly dependant on the speed of drawing electricity from the battery, and the current battery state is calculated by a Pojkert law equation.

The present prototypes of solar vehicles use lithium-ion (Li-ion) or lithium-polymer (Li-Poly) batteries because they represent the latest generation of batteries, and they have an important role in the big technological progress of solar vehicles in recent years. Lithium battery cells provide about six times more power per a mass unit than the accumulator lead batteries. These batteries enabled the vehicles of 180 kg to reach the speed up to 100 km/h. However, this lithium technology requires a special maintenance and an active survey of the voltage, current and cell temperature so the chemical instabilities and the battery life degradation could be avoided.

To maximize the performance and the range of solar vehicles, it is necessary to maximize the efficiency of the vehicle's electrical components and, at the same time, minimize the power needed for moving. The power necessary for keeping constant speed (v) and, thus, overcoming the aerodynamic resistance power, the rolling resistance and the road decline can be calculated from:

$$P(v) = P_{aero} + P_{rolling} + P_{slope} \tag{1}$$

$$P_{aero} = 0,5\rho C_d A_f v^3 \tag{2}$$

$$P_{rolling} = mgzC_r \tag{3}$$

$$P_{slope} = mgzv \tag{4}$$

where: ρ - the air density; C_d - the aerodynamic vehicle resistance coefficient (depends on the area and the shape of a vehicle); A_f - the surface of the front part of the vehicle; v - the vehicle speed; m - the vehicle mass; g - the Earth's gravity acceleration; z - angle of road's longitudinal slope; C_r - rolling resistance coefficient.

Regardless the environment, ρ, g and z are the constants which do not depend on the vehicles. The greatest power losses are the consequence of the air resistance power Paero, which is in the direct function from v^3. The aerodynamic vehicle resistance coefficient C_d depends on the vehicle area and shape. The vehicle's shape is certainly very important for the undisturbed air circulation and for avoiding the air swirling (turbulence), figure 2.

The total vehicle mass m is very important because it influences the Pslope and Prolling and it also reduces the power needed for accelerating. Because of that, it is important to minimize the vehicle mass, which was one of the reasons for adopting the new generations of batteries. Using aluminium and composite materials for making the chassis is also recommended because it considerably reduces the vehicle mass. Unfortunately, this tendency for minimizing the vehicle mass led to the fact that designers often exclude the vehicle accessories and thus directly reduce the driver's comfort. However, these discomforts are just temporary until their adequate alternatives are found.

The only mobile parts on solar vehicles are the wheels. The wheels' diameter is very important because big wheels increase the vehicle mass, they are better over the roughnesses and they require a higher gear relation in the transmission. Previous models use wheels of 40 mm to 50 mm diameter, although solutions for up to 70 mm were suggested, and then it was observed that the rolling resistance increased for about 0,07 N. The wheel diameter influences the speed of wheel rotation and, thus, on the gear transmission relation and the speed of rotation per minute and it must be chosen carefully.

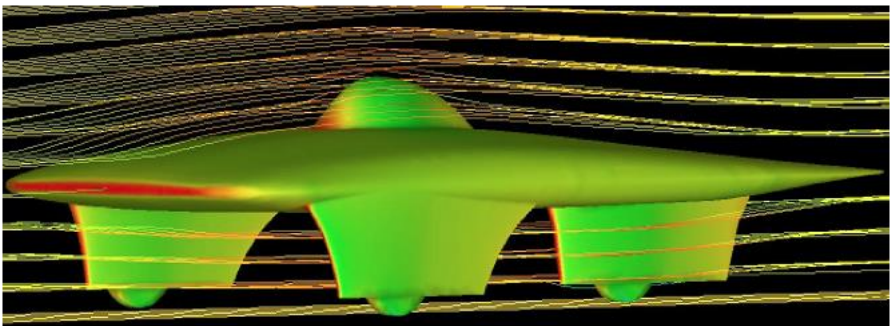

Figure 2 Display of the air flow in relation to the vehicle body

To reduce the abrasion, closed ball bearings are suggested as the protection from the impurities. It is recommended that the disc wheels should be of aluminium or of polyurethane with rubber only on drive wheels. All the inner vehicle components (including the brake system and the supporting system) are enclosed by special materials which don't disturb the flow of air. There are only few smaller openings on the vehicle for batteries' cooling and for driver's ventilation inside the vehicle.

2.2. Experience in Solar Vehicles Development

Solar vehicles have existed for a long time now, and although we cannot find them in retail at the moment, there is much interest for such vehicles. Many countries in the world develop their own models of solar vehicles with their own homologation and that shows how much they are interested in this type of vehicles. As for the current researches and solar vehicles development, it is important to mention the Ford and Mazda companies which tested the solar hybrid vehicles a few years ago and since then they have been actively working on perfecting these technologies.

Ford Reflex is a vehicle presented in public in 2006, and it’s distinctive by its solar panels which are placed in the headlights themselves. This vehicle is also equipped by an advanced electro-diesel hybrid engine with lithium-ion batteries which provide that the vehicle will use 3,6 L/100 km diesel fuel, and accelerate from 0 to 97 km/h in 7 seconds. Ford presented one more solar vehicle prototype, called C-MAX, at this year’s CES 2014 Fair, figure 3. Ford claims that it has reached the stage in which this vehicle gets 75% of the energy needed for its daily functioning from the solar plates placed on the roof of the vehicle. They achieved this by coating the panels with lenses which focus and increase the solar energy, so this vehicle functions even in bad weather conditions. The vehicle should be exposed to sunlight 7 hours a day to be charged completely. With such charged battery, the vehicle can travel up to 33,8 km with no problems before the battery empties.

Figure 3 Ford C-MAX

Mazda Senku is a vehicle presented to the public as a concept in 2005, and its solar panels were on the roof, too. This Mazda hybrid system is one of the first possessing the START-STOP function which enables less fuel consumption in urban areas, and thus a reduced emission of greenhouse gases. In this vehicle, solar cells are placed on the far end of the glass roof which enables the uninterrupted flow of light to the layers with the solar cells. These cells represent the next generation of the technology which provides the low costs of the whole solar system on one side, and on the other is very convenient for installation and because of the transmitted light percent. This whole system is actually the evolution of solar roofs (first of the kind) which Mazda developed and applied on its vehicle Sentia in 1991. The purpose of these roofs is to provide help in the form of additional electrical energy to the hybrid system in the vehicle. While the vehicle is parked, or stationed for any other reason, this system is the primary source of electrical energy. Cadillac Provoq is a vehicle presented in 2008, which uses solar panels to power the on-board accessories, such as and the audio system, the interior lighting etc.

It is also necessary to mention the French automotive manufacturer Venturi which made considerable efforts in creating the vehicle of the future. One of these prototype vehicles was presented at the Paris Motor Show in 2006. This electric vehicle uses, in combination, solar energy, wind energy and batteries, which power the vehicle together. Solar panels are placed on the roof of the vehicle, while the vehicle also uses the wind energy which the turbines automatically transform into electricity used for powering the vehicle and its batteries. However, this vehicle is relatively slow because it cannot go faster than 48 km/h.

Application of solar panels is also expanding in the field of load vehicles, buses, motorcycles and other vehicles in road traffic. At load vehicles, there are great capacities for battery and panel storage, both in the passenger and the load part of the vehicle, figure 4.

Figure 4 An example of placing solar panels on a lorry

Although batteries occupy a certain space, there is still enough load space for basic needs in all the parts of the vehicle. At the moment, the following types of commercial vehicles powered through solar panels with one charging are developed:

- Balqon, maximum speed – 110 km/h, 240 km range;
- Boulder EV, maximum speed – 104 km/h, 320 km range;
- Zero Truck, maximum speed – 90 km/h, 160 km range;
- Enova, maximum speed – 105 km/h, 240 km range;
- EVI Trucks, maximum speed – 96 km/h, 145 km range;
- E-Star EV, maximum speed – 80 km/h, 160 km range;
- Smith Electric Vehicles, maximum speed – 80 km/h, 160 km range.

When designing a solar vehicle, the simplest possible components arrangement should be applied. With batteries laid out correctly, the vehicle stability in new generations could be improved. It primarily refers to the vehicle gravity centre which influences the vehicle stability when it passes the curves. This should be taken care of considering that the new types of solar vehicles are becoming bigger and more massive.

3. SOLAR ROADS

In December 2008, the first solar photovoltaic system was released on a highway in the state of Oregon, in the USA. That 104 kW system of 594 solar panels produces one third of energy needed for interstate highway lightning, which showed that the solar panels could be installed into the roadways. The solar road is an intelligent road which supplies pure renewable energy and it's safer for driving. There are examples in the world of installing panels on the parking lots where batteries could be charged.

Now the powering of electric vehicles while they are crossing over the solar panels by mutual inductivity is being researched. Although it cannot supply enough electrical energy (in the current investigation phase) to power the moving vehicle completely, it will surely increase its autonomy.

If one fast food restaurant chain places solar panels on its parking lots throughout the country, electric vehicles will be powered on these parking spaces, which can considerably increase these vehicles' autonomy and make them more practical. It will also attract more users who will eat or shop in their while the electric vehicles are being powered on the parking spaces. As the number of buyers grew, the electric vehicles would become more practical. That way the other enterprises will see the advantages of paving their parking lots which enables them to stop paying for the electrical energy from the classic sources.

3.1.The non-contact Magnetic Charging

Scientists from the Korean Advanced Institute of Science (KAIST) developed an electrical transport system (the so-called OLEV - Online Electric Vehicle) where vehicles get their energy from cables places underneath the road surface (30 cm under it), and the energy itself is wirelessly sent to the vehicle on the road. This system was applied for the first time in the Korean city of Guma, where the first wireless electronic bus has been operating since July, 2013, figure 5.

Figure 5 A bus being supplied from the road

Of course, in the current state, this system is powered from the city electrical power supply. However, this is just the first step towards the further technology development. The ways to make this system work together with solar roads are being considered. That way this system would become self-sustainable and independent of the city power supply.

3.2. Management and Traffic Safety

Each solar panel is 4 x 4 m, it contains a microprocessor which monitors and controls the panel, which then communicates with the surrounding panels and vehicles passing over it. This means that there is a communication device on the road at every 4 metres. With this kind of control, the possibilities of managing the road by dotted lines are great since you can 'travel' along the vehicle at a certain speed limit. If a car moves faster than the lines, it means that it moves faster than the limits. If the line is faster than the vehicle, the vehicle moves too slow. You can keep the desired speed without looking at the speedometer. The road can warn you about the upcoming congestions and even recommend the way to avoid them. The destination can be entered into the GPS device and the arrow appearing on the road can navigate the driver, instead of the previous audio navigation.

Unlike the non-lit roads by which we drive at night, solar roads will have the LE diodes which will 'colour' the lanes, and they can be instantly changed if needed. Many people have the problem of vision, especially when they are blinded by the headlights of a car coming from the opposite direction or when it's raining. If the vehicle crosses the dividing line several times at a certain section, the LED ring, which will travel with the vehicle unlimitedly, can be formed around it. This will warn the other drivers about the potential danger and the law enforcement officers about the potential problem. Solar roads can considerably reduce the number of casualties, the night driving will be safer and, thus, the number of accidents caused by the speed unadjusted to the road conditions reduced. This can result in reduced insurance proceedings for all the traffic participants.

There is no need for the roads to use the electrical energy in the periods when there are no cars, so the intelligent roads would activate the LE diodes just if they sensed a car on its surface – for example, 1000 m before the vehicle and 500 m behind the moving vehicle. In this way, the drivers will know that a car is approaching from the opposite direction by seeing the light on the road. The LE diodes can be programmed to move parallel with the vehicles at the limited speed, warning the driver if he moves too fast. Diodes can also be used for writing the letters on the road, for warning the driver about the animals on the road, about the detour, the accident, the road works, etc. The central control station will be able to change the lines and letters instantly, thus reducing the traffic digestion and making roads safer and more efficient. The cities will be able to change the road and parking space signalization to adjust them to their needs.

3.3. Economical Aspects of Solar Roads Construction

The price of constructing highways with classical roadway construction has increased several times in the last few years. In our country, the price of liquid asphalt is relatively low and it is about 70 E/t at the production site and about 60 E/m^3 depending on the concrete brand. The price of material for solar road construction is very high for now. There are some ways to realize more income: by energy generating, transporting purified water from the local communities or agro-centres, for lightning commercials, payments at parking lots, payments of vehicle charging on them or at special stations etc.

It is hard to determine what could be expected from revenue collection, but it is definitely true that electric energy generation provides the best effect, as following:

- average price of electrical energy was 12 cents a kWh in the USA in April 2009,
- the electrical energy price increased in the previous period for 35% till 2009,
- the target price for a solar panel is 10 000 dollars and its lifetime is 20 years.

At a present price in the USA, which is 12 cents a kWh, a solar panel could generate 10000/0,112=83,333 kWh, so it would pay for itself in 20 years. This is the longest possible scenario because it suggests that the price of energy will not increase significantly in the next 20 years. To generate 83,333 kWh, which is the figure a solar panel needs to pay off, the daily production of 11,4 kWh is needed (by current prices).

When the energy of sun reaches the earth's surface, it has declined for 1000 W by a square meter at noon on a sunny day. All over the planet, in average, 24 hours a day in a year's time, each square meter gathers energy equivalent to a barrel of oil every year, ie, 4.2 kWh energy every day (average for the whole year). If the solar panel dimensions are 3,66 m, and the surface 13,4 square meters, at the average energy of 4,2 kWh per square, we get 56,28 kWh per panel. If we use panels of 18,5% efficiency, we get 10,41 kWh per panel theoretically. At the given values, it takes a bit less than 22 years to pay off a solar panel without a significant increase in price of electrical energy during the panel exploitation. If the panels had a little better coefficient of sun energy exploitation, it would shorten the payoff deadline. One of the important characteristics of solar panels is that majority of them can be reused while some components (solar cells, condensers, LE diodes…) and must be replaced.

To compare the construction expenses between the present road constructions and the solar roads more precisely, we should compare the prices of asphalt and/or concrete surfaces, the expenses of thermal power plants operation, the system for transmission and distribution of electric energy with the prices of constructing a solar road. Besides, the elimination of power plants which use fossil fuels will cut the carbon dioxide emission in half and thus create an indirect effect which mustn't be neglected in cost analysis. Providing stations for electric vehicles charging anywhere by the road will open the door for eliminating the internal combustion engines which are responsible for most emission of pollutants. Besides, solar roads convey energy, not from a centralized spot, as with power plants, but from its own network for electrical energy production and it can also transmit signals for cable TV, telephone, fast internet to every home and the institutions connected to the network by access roads and parking lots. Basically, a solar road becomes a transmitter for all the electro signals and signals carrying data.

3.4. Some Dilemmas about the Solar Roads

Are solar roads a utopia or not? Wouldn't it be wiser to build canopies over the roads to hold the solar panels? Or just to place the panels on the north side of the road, facing the sun?

No, it would be much more expensive because we would still have to pay for the existing road infrastructure. Spending the money already designated for classical roads on the solar roads is being planned. If we built roads with classical road construction and canopies over them or if we put the side panels, the price would multiply. Most characteristics of solar roads would also be lost, such as the LE diodes lighting in night rides. Side panels wouldn't help in road protection from snow and ice, so the cities in the north would still have expenses for cleaning the snow and the accidents caused by unsafe road conditions. Many other features would be lost, such as saving lives of millions of animals, self-healing decentralized powering net, all aspects of an intelligent road, reporting potential problems, crime and terrorism reduction etc.

What is the adhesion like? Automobiles slide on the wet asphalt, not to mention the wet glass. What will happen to the solar roads surface when it rains?

Everybody figures a car sliding and losing control on the wet glass. But, one of many technical characteristics of the upper layer is that its texture provides adhesion, at least the same as the existing asphalt, even when it rains.

How to keep a solar road surface clean?

There is something called the self-cleaning glass. It is a special type of glass with the surface which cleans itself by natural processes. It cleans itself in two phases: the photo catalytic stadium of the process breaks the organic dirt from the windshield using the ultraviolet air spectrum in the sunlight and makes the glass hydrophilic (otherwise it is hydrophobic). During the glass hydrophilic state, the rain washes the dirt away leaving the surface clean, since the hydrophilic glass distributes water evenly on its surface.

It is yet to be seen whether this process could keep the solar roads clean in operational conditions, but it will certainly help in solving the problem. There will be obstacles, such as the oil spill, sand storms, etc. The worst possible scenario is: if everything else fails, the snow plows can be replaced by street sweepers (vehicles with rotating brushes). This is for the case of the worst possible scenario and only in the case when the self-cleaning glass cannot perform its function well enough.

Some of the roads in the environment never see the sunlight. Does it mean that we shall never see solar roads in our neighbourhood?

No, it doesn't. Solar roads will be installed in tunnels and under the bridges, regardless the fact there won't be any sunlight there. By the calculation, three times more energy than needed would be produced. Theoretically, it means that only one third of panels should be exposed to sunlight. They would still glow, melt ice and snow, report problems, using the energy collected by the lighted panels.

4. CONCLUSION

Sunlight is the greatest potential source of renewable energy in the world, but it can easily happen that this whole potential remains unrealized. Not only that solar panels do not function at night, but during the day their power rises and falls if the clouds pass over them. That's why most solar panels are connected to the power supply network. During the sunny days, when the conditions for the panels are ideal, the users can sell the extra energy to an electricity distribution company, but generally, all of them have to be in the network during the night or when the clouds darken the panels.

There are many applications showing that the electronic vehicles are more convenient for using than the classical ones. Although investing in solar panels for the vehicles seems expensive, this investment pays off through great fuel savings, savings for the reduced maintenance etc. However, the prices of solar panels still aren't low enough to justify their usage with automobiles and other vehicles, so these panels are mostly used in construction works.

Moving to solar energy (instead of using fossil fuels for getting electrical energy) and choosing electric vehicles by a growing number of users, means that the beginning of the end for fossil fuels usage is at reach. The greatest advantages of solar vehicles are: the zero emission of harmful gases, the solar vehicles engine makes no noise, the dependence on fossil fuels is greatly reduced, the servicing and maintenance of these vehicles is much simpler, and thus cheaper. The batteries developed so far are already capable of satisfying 80% of our daily needs for transport. It should also be mentioned that the next generations of batteries are being developed and they will be capable of competing with the mileage realized by vehicles with reservoirs full of fuel.

A solar road will pay off through electric power generating. The same amount of money now being used for classical roads production will be used for building solar roads. The demand for electrical energy produced in hydro and thermal plants will decline and all the money invested in them could be redirected to solar roads. In addition to that, the price of energy distribution should be calculated (transmission lines, transformer stations etc.)

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