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Case Study of a Solar Power Installation for an Automated Transit Network in San José

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Abstract

The Sustainable Mobility System for Silicon Valley (SMSSV), also known as the Spartan Superway, is a project to develop a grid-tied solar powered Automated Transit Network (ATN) system.

Recent work has focused on analyzing the power requirements and designing the solar power system for a potential implementation of ATN in the city of San José. Extensive use of the System Advisor Model (SAM) software from the National Renewable Laboratory (NREL) has made it possible to estimate how much solar PV is needed to run the system 24/7 and be zero net-metered (on average) over a calendar year.

SAM estimates the number as well the total area of PV needed. Considering losses from shading and soiling, it is possible to predict how much of the POA (plane-of-array) energy will be available for the transportation network and how much can be used for other applications.

Modeling results show that to operate approximately 90 vehicles over the 14 km guideway 24 hours a day requires 19,600 monocrystalline solar panels with an area of 38,300 m².

Keywords: *Automated Transit Networks (ATN), Personal Rapid Transit (PRT), sustainable energy, photovoltaic cells, System Advisor Model (SAM)*

1. Introduction

San José State University started the Sustainable Mobility System for Silicon Valley (SMSSV), also known as Spartan Superway, in 2012. It addresses sustainable mobility through the use of a solar-powered automated transit network (ATN), sometimes referred to as personal rapid transit (PRT) or pod cars. The Spartan Superway solves the problems of traffic congestion, accidents, high vehicle costs, environmental degradation, and significant dependence on fossil fuels for transportation.

The United States Energy Information Agency (EIA) estimated in 2011 that energy sources used in the US were 38.1% oil, 20.8% coal, and 22.9% natural gas - in other words 81.9% of our energy came from hydrocarbons with harmful emissions (EIA, 2011). The objective of the authors' research is to power the Spartan Superway ATN completely using solar energy, drastically reducing the amount of toxic materials, i.e., batteries, fossil fuel, coal, etc., that are used by other modes of transit. The integration of solar power into the Superway encompasses solar panel mechanical design, solar panel orientations and material, relevant energy consumption and production calculations, and the electrical system design.

Progress has been made in: determining the general power consumption for the Spartan Superway, solar panel array designs, general power production of PV panels, electrical system and electrical rail traction

(wayside pick-up). A full-scale test track is being designed, so that the complete system can be validated and refined. The rest of this paper will summarize results of research to date.

2. Sustainable Mobility System for Silicon Valley (SMSSV)

The SMSSV, also known as Spartan Superway, consists of vehicles that are suspended below and move along an elevated guideway above which solar PV panels are attached. It is expected that vehicles will carry four to six passengers. Operation of the vehicles can occur 24/7, because the solar system will be tied to the grid. It is conceivable that vehicles could also be used for material transport when passenger transport is low (such as at night).

Work on this project since 2012 has been carried out by students, primarily from San José State University but also including international students. The groups are divided into teams focused on Bogie, Propulsion, Steering and Braking, Active Suspension, Cabin, Wayside Power, Guideway Structural Analysis, and Power Analysis.

3. Methodology

3.1. Scenario analysis

The initial design case consists of the network shown in Figure 1, that connects the south and north campus locations of San José State University and the Tamien Cal Train and VTA Light Rail stations. Table 1 lists the specifications for the N-S campus network.

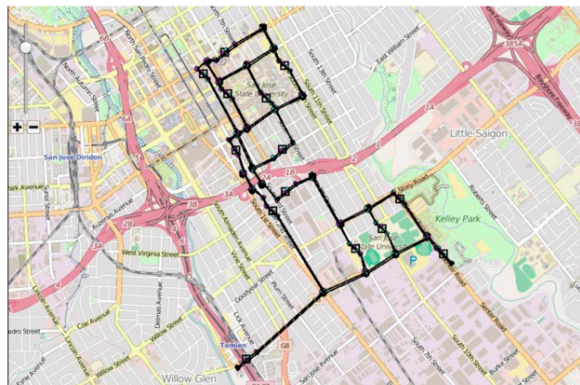


Fig. 1: Guideway placement for the SMSSV in San José

Tab. 1: Network specifications

North-South Campus network	
Total length	14.400 Km
Available area	43,200 – 57,600 m ²
Distance between N-S	3500 m
Number of vehicles	85-95
Number of stations	26

Automated transportation networks require control of the spacing of vehicles moving on the guideway. One control approach is known as synchronous moving-cell control. This approach assumes that vehicles travelling along a given link in the network occupy hypothetical slots (Rumsey, 1973). A recent study on ATN for the city of San José done by the Aerospace Corporation found that congestion on the network would occur if the maximum number of slots occupied by ATN vehicles exceeded about 70% of the total number of slots (Paige, 2012). This finding, combined with analysis of data from the University’s Park and Ride shuttle (which moves people between a parking lot near the south campus to the north campus), guided the determination of the number of vehicles, which was in turn used to calculate the required energy needed to run the system.

3.2 Power estimation

Equation 1 shows how to calculate the average energy required to move a train of n_T vehicles - a distance D_s over a time duration from $t = 0$ to t_s . The equation is given by (Anderson, 1978):

$$E(t_s) = \frac{1}{\bar{\eta}} \left\{ (1 - R)n_T \frac{M_V V_L^2}{2} + \frac{1}{2} \rho C_D A_V \left[(V_L^2 + \langle V_w^2 \rangle) D_s - \frac{V_L^4}{2a_m} \right] + n_T M_V \left[C_1 D_s + C_2 V_L \left(D_s - \frac{V_L^2}{3a_m} \right) + gz \right] \right\} + n_T P_{aux} t_s \quad (\text{eq. 1})$$

Table 2 lists the variables needed in the calculation.

Tab. 2: Variables to account for energy required by a (n_T) number of cars to move from $t=0$ to t_s

Quantity	Symbol	Unit	Quantity	Symbol	Unit
Motor efficiency	η	%	Auxiliary power – Outside required power	P_{aux}	W
Energy recovery factor – Regenerative braking	R	%	Distance between stops	D_s	m
Number of vehicles	n_T	-	Maximum acceleration		kg m^{-3}
Vehicle mass	M_V	Kg	Road rolling resistance:		
Operational speed	V_L	m s^{-1}		C_1 C_1	m s^{-2}
Air density	ρ	Kg m^{-3}		C_2 C_2	s^{-1}
Coefficient of air drag	C_D	-	Change in the elevation during the trip	z	m
Wind speed	V_w	m s^{-1}			

The velocity profile for a trip cycle is shown in Figure 3:

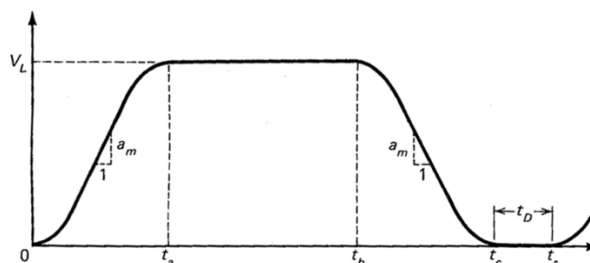


Fig. 3: Station-to-Station Velocity Profile (from Anderson, 1978)

The vehicle begins to move at $t=0$, reaches maximum velocity at $t=t_a$, cruises at constant speed until $t=t_b$, decelerates and reaches zero velocity at t_c , waits at a station for a time $t=t_D$ (called the station dwell time), and repeats the cycle. Equation 2 defines the station-to-station time, t_s (Anderson, 1978):

$$t_s = t_D + t_a + (t_c - t_b) + (t_b - t_a) \quad (\text{eq. 2})$$

As this method consider a train of vehicles instead of single cars running along the guideway, the first step is to calculate the amount of energy for $n_T = 1$. Next, the values of energy consumed by air resistance for all the cars as well the road rolling resistance and the energy recovered using regenerative brakes are summed, and this sum is multiplied by the actual number of vehicles running on the guideway.

3.3 Assumptions and System Advisor Model (SAM) Database

The System Advisor Model (SAM), developed by the National Renewable Energy Laboratory (NREL), was used to develop the analysis of the solar power system (<https://sam.nrel.gov/>). The output from SAM shows the total area and number of solar panels needed.

To proceed with power consumption calculations, it was necessary to assume certain parameters. The first

step was to access the weather data from the city of San José to estimate the mean wind speed over the year. To estimate the amount of energy needed to move the car at 13.4 m/s (30 mph), it was also necessary to define the air drag coefficient of the vehicle cabins used on the guideway.

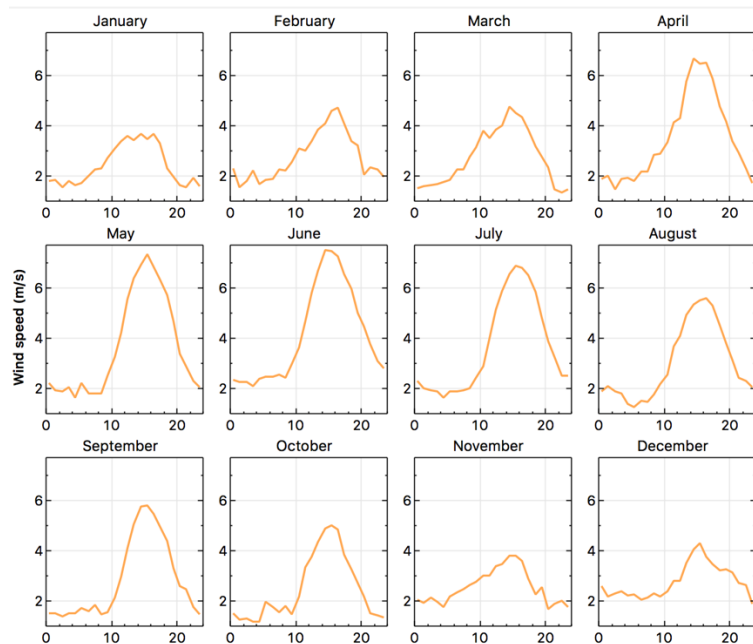


Fig. 4: San José's profile of average wind speed per hour (data from SAM)

Analyzing San José's profile of average wind speed for the N-S network area, a conservative, peak annual wind speed of 9 m/s was assumed. The coefficient of air drag was found using an airflow model in Solidworks, which came out to be 0.65. Surprisingly after verifying all the energy losses for the system, it turns out that 53% of the losses are due to the air drag.

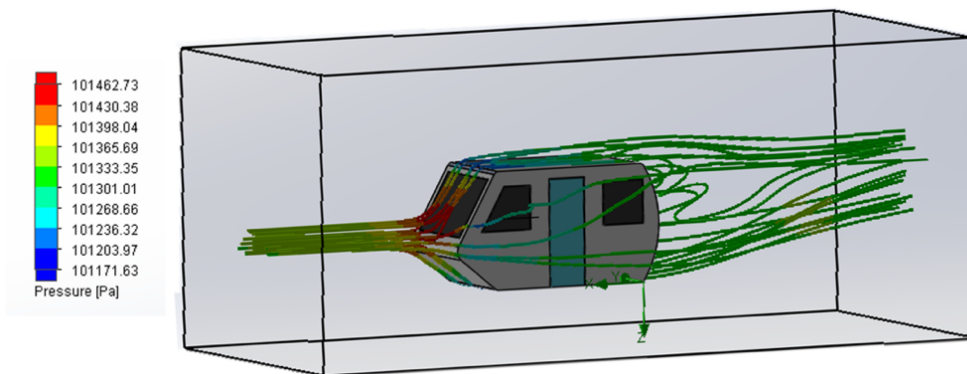


Fig. 5: Airflow model of cabin flow simulation

After considering the aerodynamics of the pod car, it is necessary to verify how much energy will be recovered by a regenerative braking system and how much it is lost by the efficiency of the electrical drive motor. The road rolling resistance was also taken in consideration on this analysis. For simulation purposes, an energy recovery factor of 15%, an electrical motor efficiency of 85%, and the rolling resistance for heavy rail transit (Anderson, 1978) was used in the calculation.

To properly estimate the area of PV required and the number of inverters needed to satisfy the power requirement, three different tracking and orientation approaches were considered. The first one uses a fixed solar panel orientation, the second one uses a single-axis tracker, and the third uses a dual-axis tracker.

4. Results


Using equation 1, the energy consumption of all the vehicles is approximately 28,490 kWh per day, which equates to 10,398,940 kWh per year. The values of the variables used in the calculation are shown in Table 3 below.

Tab. 3: Variables and their values used to calculate the energy consumption of vehicles.

Variable	Value	Unit
Gravitational acceleration	9.81	m/s ²
Auxiliary power	3500	kW
Time	293	s
Efficiency of the motor	0.85	%
Number of vehicles	150	-
Mass (vehicle)	1900	kg
Operating speed	13.4	m/s
Air density	1.225	kg/m ³
Coefficient of air drag	0.51	-
Wind speed	9	m/s
Average distance between stops	3500	m
Maximum acceleration	4	m/s ²
Rolling resistance coefficients		
C ₁	0.0095	N/kg
C ₂	0.0004935	Ns/mkg
Change in elevation	10	m
	Value	Unit
Pod car daily energy consumption	3.97x10 ⁶	J
	13.49	kW
Total vehicle daily energy consumption	28,490.2	kWh
Total vehicle yearly energy consumption	10.40x10 ⁶	kWh

Considering the annual consumption of 10.40 x 10⁶ kWh listed in Table 3 above, calculations determined that a 7045 kW DC PV system would be needed. To get an estimated number of panels required, the panel module was assumed to be a SunEdison SE-R360EzC-4y 360W (18.41% efficiency), and the inverter was assumed to be an Advanced Energy Industries: AE 500NX-HE 480 VAC. Using SAM, and the assumptions just described, the model predicts that 19,600 panels are required, which have a total area of 38,300 m². This could be supplied by using a canopy of panels approximately 3 m wide over 89% of the 14 km guideway network. The total installation cost for the system is estimated to be \$17.4 million as shown in Table 4 below.

Tab. 4: SAM’s Photovoltaic Systems Report summarizes the performance of our panels (modules) and Inverters as well as the necessary constraints for our desired array size.

System Advisor Model Report		
	Photovoltaic System Commercial	7.0 DC MW Nameplate \$2.46/W Installed Cost
		San Jose Intl Ap, CA 37.37 N, -121.93 E GMT -8
Modules	Annual Results (in Year 1)	Array
SunEdison SE-R360EzC-4y	GHI kW/m ² /day 5.0	Strings 1,629
Cell material Mono-c-Si	POA kW/m ² /day 4.0	Modules per string 12
Module area 2 m ²	Net to inverter 10,778,000 DC kWh	String voltage (DC V) 460.8
Module capacity 360.2 DC Watts	Net to grid 10,403,000 AC kWh	Tilt (deg from horizontal) 30.0
Quantity 19,548	Capacity factor 16.87	Azimuth (deg E of N) 180
Total capacity 7 DC MW	Performance ratio 0.72	Tracking no
Total area 38,235 m ²		Backtracking -
Inverters		Self shading no
Advanced Energy Industries: AE 500NX-HE (3159502-XXX)		Rotation limit (deg) -
Unit capacity 500 AC kW		Shading yes
Input voltage 330 - 600 VDC DC V		Snow no
Quantity 13		Soiling yes
Total capacity 6.5 AC MW		DC losses (%) 4.4
DC to AC Capacity Ratio 1.08		
AC losses (%) 1.0		
	Project Costs	
	Total installed cost \$17,354,106	
	Salvage value \$0	

It is important to note that the analysis above assumes that all panels are at a fixed tilt angle of 30°. If however, a single-axis tracking system was used, this would increase the collected energy by about 17.4% result in a 5815 kW DC system, which would consist of 16,140 panels (31,600 m²) and would save approximately \$3 million in installation cost.

If a dual-axis tracking system was used, the system would collect 20.9% more energy than the fixed tilt system and would result in an array size of 5570 kW DC. This system would have 15,500 panels (30,300 m²). To account for the energy consumption and tracking system installation cost, the Helios tracking system (<http://heliotrack.com>) was assumed. The annual energy consumption of this tracking system is approximately 0.127 kWh for a 1-axis tracker and 0.255 kWh for a 2-axis tracker. Each tracking system consumes 0.6 watts and works for approximately 3 minutes every 8 hours, which equates to 2160 J every 8 hours. SAM's average daylight hours of 9.3 in San José was used to calculate the amount of energy consumed per day per tracking system, and the number of tracking systems needed was calculated assuming one tracking system can move 5 panels. The overall energy consumption of the tracking systems can be satisfied by just an additional panel for a 1-axis system and two additional panels for a 2-axis system.

Tab. 5: SAM's solar panel (module) calculation for a Single-Axis system (left table) and a Dual-Axis system (right table) for the North-South Campus track.

Modules		Modules	
SunEdison SE-R360EzC-4y		SunEdison SE-R360EzC-4y	
Cell material	Mono-c-Si	Cell material	Mono-c-Si
Module area	2 m ²	Module area	2 m ²
Module capacity	360.2 DC Watts	Module capacity	360.2 DC Watts
Quantity	16,140	Quantity	15,456
Total capacity	5.8 DC MW	Total capacity	5.6 DC MW
Total area	31,569 m ²	Total area	30,231 m ²

Development of a test track for Superway is also underway. Assuming a guideway length of 650 m, with one active vehicle moving on the guideway 24 hours a day, the estimated energy consumption per year is approximately 5.32×10^4 Kwh. Assuming 150 m between stops, and the SunEdison SE 360W panel for the PV canopy, the required numbers of solar panels needed to satisfy the daily energy consumption would be approximately 94 to 125 depending on fixed or tracking systems shown in Table 6 below.

Tab. 6: Test track cost analysis comparing a fixed system, 1-Axis system, and 2-Axis system.

Tracking System Energy Analysis	Fixed	1-Axis system	2-Axis system	Unit
% of Optimum	-	22.22%	24.44%	%
Total Energy Consumed by Pod	5.32×10^4	5.32×10^4	5.32×10^4	kWh
Annual Consumption for Helios tracking system	0	.127	.255	kWh
Annual Consumption for Helios tracking system	0	2.45	4.76	kWh
Panel/annual production	4.03×10^2	5.53×10^2	5.69×10^2	kWh
Number of panels to compensate tracking system	0	1	1	-
Number of panels	124	97	94	-
Area of Panels	248	194	188	m ²

In Table 6 above, the annual energy consumption of each tracking system is compensated by just one additional panel. The total cost is the sum of cost of installation and the cost of the tracking system (if applicable). The optimization is found by calculating the % difference between the fixed system's and each tracking system's necessary array size. The total panel area is approximately 248 m² for a fixed system, 194 m² for a 1-axis system, and 188 m² for a 2-axis system. In each case, the required area of panels can fit above the guideway over the length of the test track.

4.1 Solar Energy Production and Losses

As the amount of solar energy available in California varies throughout the year, it is also important to define how Superway will be integrated with the electric grid in the city of San José. It is assumed that the grid will be charged throughout the sunlight hours and power the transit system during non-sunlight hours. Figure 7 shows the expected yearly power generation profile.

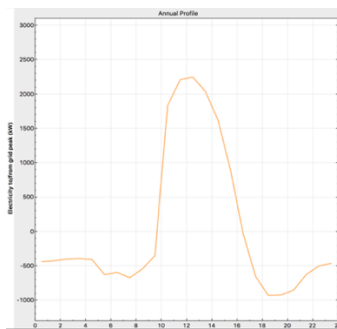


Fig. 7: Annual Profile of Electricity to/from grid peak (kW)

The monthly energy production considering a fixed orientation of the solar panels on the proposed guideway is shown in Figure 8. As expected, the summer months produce the most energy. The grid will receive electricity throughout the sunlight hours and power the transit system during the non-sunlight hours. During the months that the energy produced is not enough to meet all the power requirements, the mobility system will be compensated by the period of the year which there is more energy available.

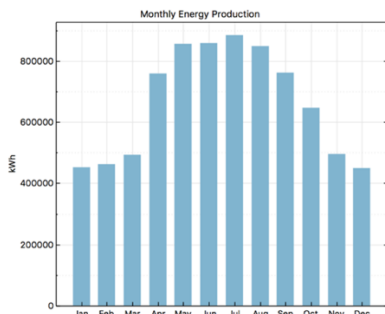


Fig. 8: Monthly Energy Production in kWh

The expected energy losses are related mainly to the efficiency of the selected solar panel, shading, and soiling. The Sankey diagrams generated by SAM below break out the percentage of loss considered in each different tracking and orientation scenario. The maximum percentage of losses due to shading and soiling are about 25% of the nominal Plane-of-Array (POA) (kWh).

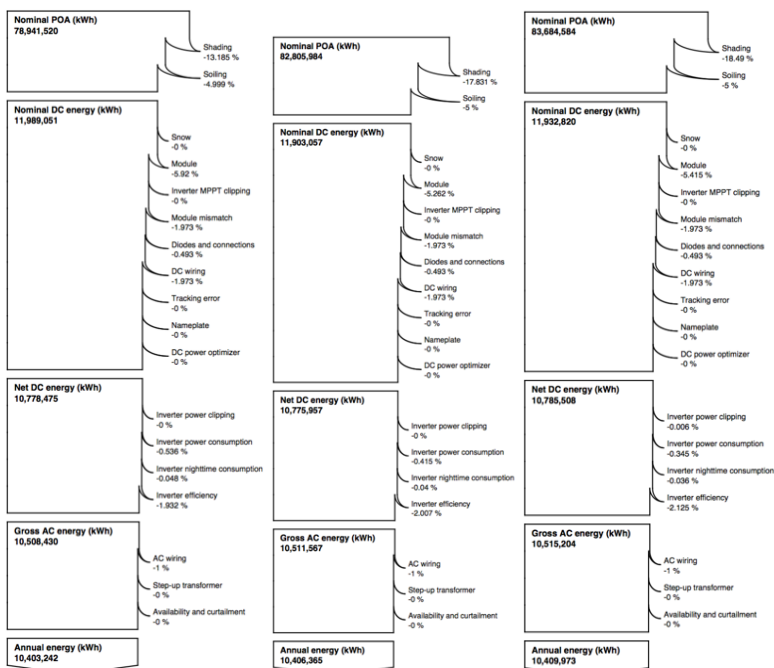


Fig. 9: Sankey Diagram for North-South Campus network for three different solar panels tracking options: fixed, 1-axis tracking system, 2-axis tracking system.

4.2 Solar Panel Design

Work is also underway to define concepts for mounting the array and improving the assembly process of the solar panels on the guideway. An important consideration for the whole solar design is to make maintenance be relatively easy.

The first concept design is a module composed of 12 PV panels arranged in an arch and fixed in orientation.

The second initial concept design supports a module composed of three thin-film photovoltaic cells bent into an arched shape. This concept integrates a tracking system that changes the tilt of the modules to guarantee an optimal tilt angle for each season of the year.

The panels have a tilt angle of at least 10° to reduce losses due soiling (Cano, 2011).

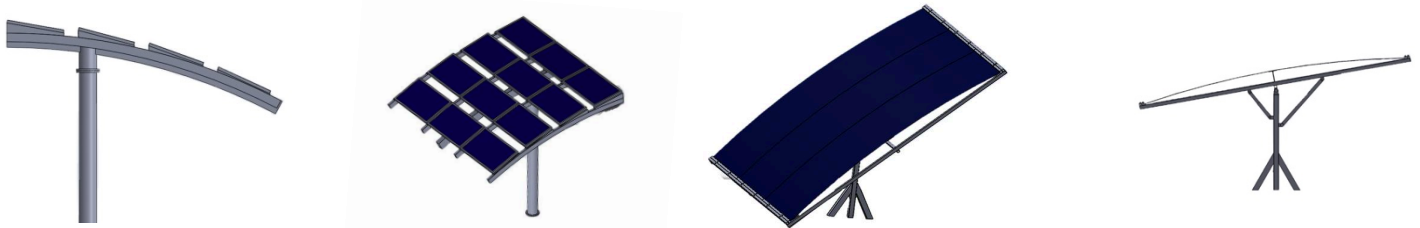


Fig. 10: Initial concepts design of the mounting array for the solar panel modules

The optimal tilt angle is a function of the latitude and the season of the year. Landau, 2015, proposed a group of equations to determinate the optimal tilt angle based on how many times during the year the tilt angle is changed.

4.3 Electrical System

Figure 11 shows a block diagram of the hardware and general electrical design. The blue lines show power supplied from the solar panels which will either load the grid or the third rail which supplies power to the vehicles on the guideway. Red dashed lines show power supplied from the city grid to the third rail. Black thick dashed lines represent voltage to motor. Inside the vehicle, the green dotted lines show power flow for regeneration from the motor. Purple dotted lines are for grounding and power return. It important to note the diagram assumes a small system with one solar array and one vehicle.

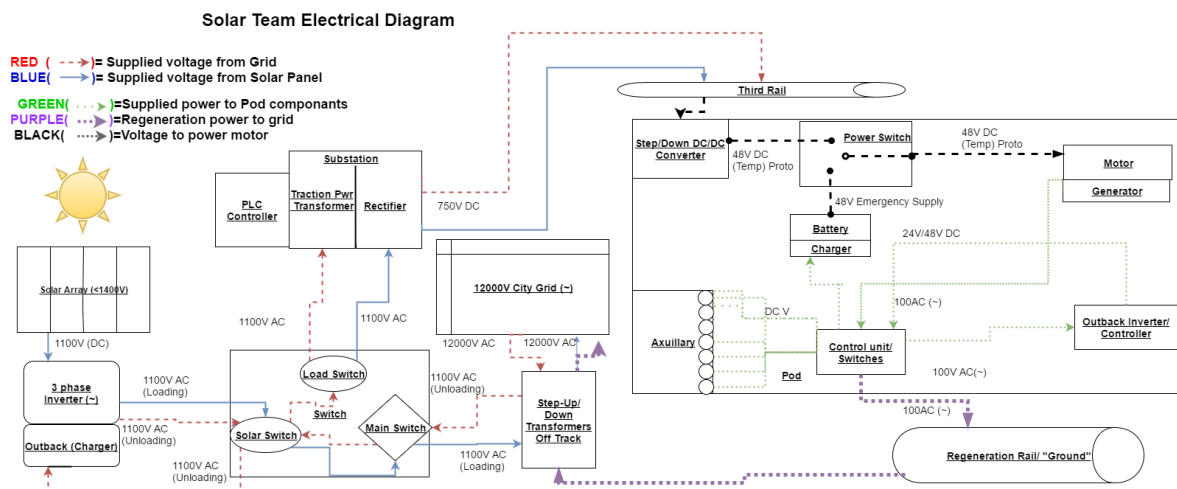


Fig. 11: Solar Team Electrical Diagram

The basic electrical diagram assumes the solar panel array supplies 1100 VDC, and this is inverted (with the same phase as the grid) to 1100 VAC. The 1100 VAC is then gated through a control switch and a series of sub-switches depending on the system component consumption. If vehicles are not consuming all the supplied power, then the 1100 AC voltage will lead to a step-up transformer to charge the city grid system. If significant power is being drawn by the vehicles, then the loading voltage from the solar array is switched to the Substation and the 1100 VAC voltage is converted to a 750 VDC voltage. During non-

sunlight hours, the assumed 12 kV AC assumed utility grid will power the system. The 12 kV AC will step-down to 1100 VAC and be synchronized in phase as the inverter using an Outback charger. The 1100 VAC is then switched into a substation the same way it would switch when being loaded by the solar array. In case the solar arrays provide inadequate power, the system will be supplied from the grid as it would during non-sunlight hours.

When the Converter/Substation receives 1100 AC voltage (from the grid or solar array), it outputs 750 VDC directly into the third rail power bus. The third rail is in turn connected to a step-down 48V DC-to-DC converter. The converter will be connected to a control switch which powers the motor. The power control switch will only switch to the battery in the case all power sources shut down. The regenerative braking system (motor-generator) will go into a control unit which will determine where the power is needed. In the case that components on board the vehicle need to be powered, the 100 VAC (assumed) voltage from the motor-generator will go into an inverter and the (assumed) 12-48 VDC will power auxiliary items. Auxiliary items will pull from the onboard battery if the regenerative voltage is not sufficient. If all components are working optimally (battery and auxiliary) then all leftover power will be sent to the regeneration rail “ground”. Unlike many three- or four-rail systems, Spartan Superway designed its regeneration rail and ground rail to be the same, thus saving energy. The regeneration would lead into a step-up transformer and charge the grid, thus completing the circuit of our system.

5. Conclusion

In summary, from the results of the power consumption simulation, the main losses of Spartan Superway project are mainly related to air resistance, around 53% of the total power consumption, followed by the auxiliary system, which consumes about 31% of overall system energy. This analysis gives an initial prediction of the overall behavior of the ATN implementation on the city of San José. Figure 12 depicts the percentage of all the losses analyzed on this simulation.

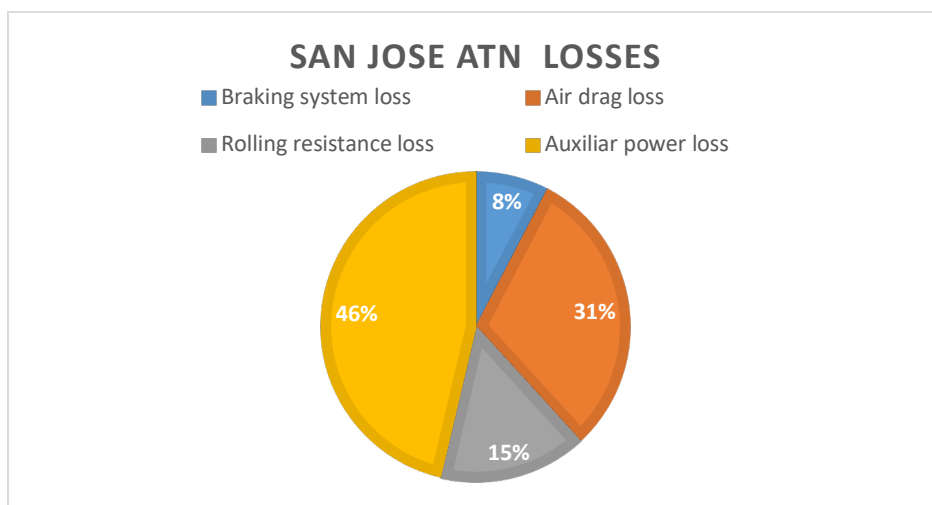


Fig. 12: Spartan Superway overall losses

It is necessary to improve the cabin design to minimize the effects of the air resistance on the pod cars. An optimistic prediction from earlier aerodynamic modeling estimated an air drag coefficient of the vehicle around 0.20 to 0.25, and if this could be achieved, it would represent a 20% gain on the overall performance. From simulations, a proposed 14 km guideway network connecting the north and south campuses of San José State University requires an installed capacity of 7.0 MW having approximately 19,600 monocrystalline PV panels.

6. Future Work

The power consumption estimation of the ATN can be automated using SAM’s Software Development Kit provided by the National Renewable Energy Laboratory. In general, estimates of power required could be

improved by refining the assumptions used in the model.

Next steps in research will focus on designing a test track in order to verify possible system failures. The main priorities include designing the guideway layout and selecting the electrical components for the power system. A detailed design of a mounting array for the solar panels accounting for ease of fabrication and ease of assembly is needed, and this should include customizing the electronic and mechanical components, such as the maximizers and mounts. A detailed financial analysis of the test track is also needed.

For the north-south campus network, more work is needed to define actual orientations of PV panels for different sections of the guideway. Other work should include determining the storage system, the size of the battery bank on each section of the track, as well specifying the vehicle batteries.

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