SAPIENZA
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Solar-powered light rail vehicle and tram systems

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1. Introduction

With recent issues of global warming, greenhouse gas emission, and depleting energy resources, relatively high energy efficiency of rail transport is one of the greatest advantages, especially in view of the emission of carbon dioxide. Nevertheless, railway transit systems have still undiscovered potential for improving the energy efficiency even farther, and one which directly correlates to reduce emissions. Development of railway vehicle with onboard energy storage capability via solar and electrical energy can offers a significant reduction in energy consumption compared to conventional electrified train with overhead power feeding system.

Putting one 300 watts solar panel on the roof of a small electric vehicle would only power about 4.5 miles per day of driving. But putting the same 300 watts panel on a solar canopy above a train track to power the train would supply 4,000 passenger-miles a year.

Moreover, improvement of energy efficiency through systematic and operational optimization can be another aspect to further improve the efficiency of railway energy.

1.1. Abstract

This project aims to develop a solar powered tram service to adopt the existing electrical tram system for city of Rome and another European city with elevated solar days. The method would be installation of the solar panels on the trams roof furthermore onboard battery with storage energy capability, using catenary as the alternative energy source.

The aim of this thesis is to investigate and identify the required power to feed the trams, the generated power through the solar panels mounted on the available area of a railcar roof as well as the regenerated energy during tram braking and the useful methods to exploiting produced energy for traction and auxiliaries.

In the first part, we will have an overview of practical projects in context of solar trains and some proposals regarding the solar light vehicles in Japan and Australia.

The thesis then identifies and calculates the needed powers of a tram with characteristics which are almost similar to the newest trams operating in Rome as a sample and the produced power through the solar panels adding to the regenerative energy from tram braking. Finally campers the demand energy and the generated ones together and talks about the benefits.

In conclusion, the thesis argues the methodology of the operation of a sample tram with solar panels on rooftop and onboard battery as energy storage space and catenary as alternative energy, particularly for rainy days and night times.

1.2. Aims

The objectives of this thesis are to

- Measure approximately the required power for a cityway II tram which operates on line 8 in Rome per entire day.
- Calculate the generated power by solar panels installed on the roof according to the number of panels that can be placed on available area of the roof and the number of sunshine hours during a day.
- Simulate the vehicle function with onboard battery which can storage released energy from braking and can recharge by solar energy too.
- Compere the demand power and the supply power by the battery.

The following scopes must be taken into consideration in a solar tram system design

- Percentage of solar power input must be maximized.
- Percentage of storage power input must be maximized.
- Delay time of tram operations must be minimized.
- Production costs for the solar power and the energy storage system must be minimized
- Energy wastage must be minimized.
- Electrical storage capacity must be maximized.

2. State of art overviews

2.1. First solar train

UNESCO heritage Himalayan Queen Train from Kalka to Shimla in northern India has become in 2012 the first train in the world to adopt solar Photovoltaic (PV) panels. 200 W PV modules were fixed on the roof of each of its seven coaches. The generated energy is stored in 2x65 AH Sealed Maintenance Free Tubular 24 V batteries. Each coach has been fitted with a 100-watt solar panel with which the coaches can function for two days without the sun and can make two trips to Shimla [1].

The generated energy is used to drive seven numbers of 6W LED lights in each of the coaches, besides provision for charging mobile phones during the five-hour journey. With the PV system and energy efficient lighting in place, a 3 KW alternator, flat belts, regulator rectifier unit, axle pulleys, alternator pulleys and flooded batteries were removed from the underframe of the coach. This reduced the weight and the speed was increased correspondingly. Moreover, the key issue of “dynamic coach balancing”, was a challenge that was successfully mastered by the engineers.

Figure 2.1: Himalayan Queen Train from Kalka to Shimla with PV panels on tops of the coaches

2.2. Solar train, economic and environmental worth

Scientists have asked the railways to consider installing rooftop solar power panels on train coaches to meet their electricity needs and curb the country's diesel consumption and carbon dioxide emissions. Researchers from the Indian Institute of Science, Bangalore, have sent their proposal to the Rail Coach Factory at Kapurthala, Punjab, after showing through a theoretical study that solar panels can save up to 90,000 liters of diesel per rake per year [2].

The study examined the feasibility of installing solar photovoltaic panels that convert sunlight into electricity on a type of rail coach produced at the RCF, Kapurthala.

They have estimated that a single rake, made up of five air-conditioned coaches, 12 other coaches, a pantry car and two power cars, relying on rooftop solar panels and making 188 forty-hour trips during a year could reduce carbon dioxide emissions by 239 tones. Their study has indicated that the additional cost of the solar panels could be recovered within three years.

2.3. Solar-powered trains

2.3.1. Belgian solar tunnel

Tunnel on Paris-to-Amsterdam line topped with solar panels to power Antwerp station and Belgian train network. The solar tunnel between Schoten and Brasschaat is the first European experience. On the roof of this rail tunnel in the high-speed line between Antwerp and the Dutch border, there are 16,000 PV panels. Every year, some 4000 trains (high-speed and domestic) can use solar energy. That's approximately the need for one full day's train traffic. The annual output of this energy project is about 3.6 GWh, which is on average the annual consumption of nearly a thousand families [3].

The 16,000 solar panels in the Solar Tunnel project cut annual CO2 emissions by some 2,500 tons.

Figure 2.2: Two-mile-long solar tunnel, Belgium

2.3.2. Arizona's sun-powered train

The idea is to start a train system that connects Tucson and Phoenix in a first phase. The concept is a high speed solar train that would cover the distance in just 30 minutes, traveling at a maximum speed of 220mph (about 350 km/h), powered solely by the sun. The cost for the first phase alone was estimated at $27 billion. The train would require 110 megawatts and would operate on a dedicated way with solar power generated from overhead panels.

Figure 2.3: Solar powered bullet train proposed for Arizona

The idea is to put the solar panels on canopies above, rather than on the trains themselves, and the train would travel under them.

2.3.3. United Kingdom

Imperial College London has partnered with the climate change charity 10:10 to investigate the use of track-side solar panels to power trains. The renewable traction power project will see university researchers looking at connecting solar panels directly to the catenary, a move that would bypass the electricity grid in order to more efficiently manage power demand from trains [4].

Network Rail is currently investing billions in electrifying the UK's railways to reduce the number of trains running on diesel fuel, curbing costs, air pollution, and greenhouse gas emissions in the process.

Combining this effort with increased renewable energy generation in the UK could significantly decarbonize train lines by 2050, according to 10:10, but in many rural areas the electricity grid has reached its limit for both integrating distributed energy generation and supplying power to train firms.

Figure 2.4: Electrifying the UK's railways

2.4. Solar light railways

Light rail is a brilliant way to make cities more compact also have the advantage of being flexible in regard to adapting to the local environment. Solar and other renewable energy sources can now compete with coal to supply power for light rail transit systems. At the same time, it's getting easier to change motorists' car use. It is possible to make a light rail completely carbon free using tram batteries that are recharged at station stops or along the route using power generated by solar energy. We now have solar power and batteries that together are cheaper than coal-fired power.

2.4.1. Vili, first solar light railcar

There is a new vehicle designed by Hungarian engineers. The locally produced Hungarian railcar with no overhead electric cables carries passengers on the 12 km line between Királyrét and Kismaros in Hungary and it has been doing so since May 2013, when it was unveiled to the public.

Figure 2.5: Vili, the Hungarian solar railcar

The 8275 mm long and 2000 mm wide pollution-free railcar has seats for 32 passengers, a top speed of 25 km/h. The onboard battery is powered by 9.9 m2 of photovoltaic panels (with estimated lifetime of 20-40 years), which are located on its roof, but it can also get energy by outer electric connectors. The train also boasts electric recovery brakes, able to recover and store part of the energy spent during braking and use it to propel the train later on.

Since this 100% environmental friendly drive does not allow high speed, the vehicles that are similar to this currently produced car can be used efficiently on short distances and narrow rail gauges. It has lower power, slower speed and they are ideal for domestic local lines.

The key technical data are reported in Table 2.1 [5].

Table 2.1: The technical data of Vili

Rail gauge:	760 mm
Car length:	7500 mm
Car width:	2000 mm
Distance between fenders:	8275 mm
Car height (w/o solar panel):	2210 mm
Floor height:	360 mm
Distance between shafts:	3500 mm
Total area of the roof plate and solar panels:	9,9 sqm
New operational wheel diameter:	600 mm
Smallest operational track radius:	50 m
Nominal speed:	25 km/h
Nominal power:	14 kW
Max power:	16,8 kW
Nominal voltage:	90 V

3. Suggested systems

In this section will be investigated two proposals regarding to solarizing the intracity tram networks in Australia and Japan with which we can notice the employed methodologies, the unsolved problems, the economic and environmental advantages and etc.

3.1. Melbourne

The project outlines the key plans in regards to the implementation and conversion from the traditional electrical power towards solar power for the trams on route 86 in Melbourne, Australia. This will result in a reduction of more than 80,000 tonnes of greenhouse gas emissions every year. This conversion not only aims to reduce the emissions of greenhouse gases, but it will also minimize the long turn running costs, resulting in an increase in revenue for Public Transport Victoria and Yarra Trams.

A requirement of 14.87 MW of power output was required to operate the trams. To ensure the lowest cost, the 260W Jinko Solar Panels had been selected for this application due to its price. A thorough cost analysis had therefore determined that 34.2% of the required 15MW power to operate the trams was generated by Solar Roadways Panels, 8.73% of power generated from the rooftops of the tram depots and 58.26% of power generated from the solar farm.

3.1.1. Determination of tram power usage

Following data was taken into consideration to achieve an approximate calculation [6].

- Power usage of tram: 12 MJ per vehicle km;
- Approximate distance of route 86 (in one direction): 21.8 km;
- Time taken for a tram to complete one direction trip: 1 h + 17 min (1.28 h)
- General power usage of tram for one way = 12 MJ × 21.8 km = 261.7 MJ = 72.7 kWh
- Power usage of one tram for one way = 72.7 kWh / 1.28 h = 56.8 kW
- Frequency from Waterfront City Docklands to Bundoora RMIT: 133 trips/day
- Frequency from Bundoora RMIT to Waterfront City Docklands: 129 trips/day

Therefore, the approximate power required to operate the entire route for a day can be determined as 56.8 kW x (133 + 129) trips/day = 14,877 kW/day

To ensure that losses are accounted for, a power requirement of 15 MW was taken into consideration.

Figure 3.1: Operated trams on route 86

3.1.2. Solar panel specifications

To meet the power requirement of almost 15,000 kW/day, the JKMS260P solar panels had been chosen for this application:

- Manufacturer: Jinko Solar
- Dimensions: 1,650 mm (L) x 992 mm (W) x 45 mm (T)
- Rated Power: 260 W (at standard conditions)
- Weight: 19.7 kg
- Quantity Required: 57,600 panels

Given these specifications, the area to be covered can be determined based on the following calculations.

$$Required\ area = 57{,}600\ panels \times 1.650\ m \times 0.992\ m = 94280\ m^2$$

Therefore, the solar panels must cover 94280 m^2 (approximately 23.29 acres) to produce the required amount of power.

Figure 3.2: Solar farm example, South Australia

Table 3.1 shows the summarized information about Melbourne's solar tram project.

Table 3.1: Melbourne's solar tram project

Route properties	21.8 km, 262 one way trips
A tram demand power	12 MJ per Km
Total demand power	15 MW per day
Required solar panels	57600
Required area	94280 m^2

3.2. Japan

In this system, solar cells are installed on the roof of the platform. Wind turbines and water wheels are built around the station. Electric double layer capacitors (EDLCs) are installed at the station and always charged by renewable energy. EDLCs are also mounted on the railcar. When the railcar stops at the station, EDLCs of the railcar are rapidly charged from EDLCs of the station.

3.2.1. Energy need

The battery driven light rail vehicle developed by Railway Technical Research Institute consumes 8.9 MJ/km = 2.5 kWh/km [7]. Assuming that interval between stations is 500 m, a railcar needs 1.3 kWh to reach the next station.

If we assume the frequency of 6 trains/h and railcars are operated for 18 h/day, the power generation capacity of 270 kWh/day = 99,000 kWh/year is necessary at each station.

Figure 3.3 shows the schematic diagram of this system.

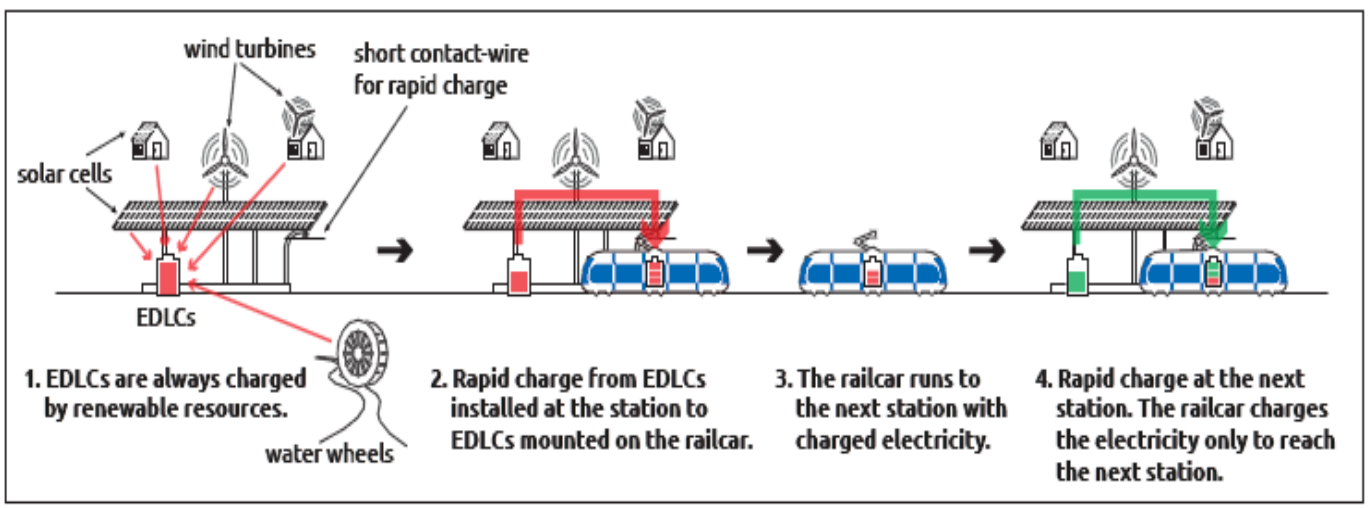

Figure 3.3: Schematic diagram of power supply system

3.2.2. Photovoltaic generation

In Japan, the amount of power generation of the solar cells per year can be calculated the rough estimate in *rated power* [kWh] × *1100* [hours].If all required electric powers of 99,000 kWh are supplied by the solar cells, they are rated at about 90 kW. When using the Heterojunction with Intrinsic Thin-layer (HIT) solar cells (energy conversion efficiency: 19%), about 470 square meters is required.

Should a roof of 2 m x 30 m be installed at each station and the whole surface is covered with HIT solar cells, about 13% of required electric power is obtained. The remaining part being fulfilled by solar cells, wind turbines and water wheels which were installed near the station as shown in Figure 3.4.

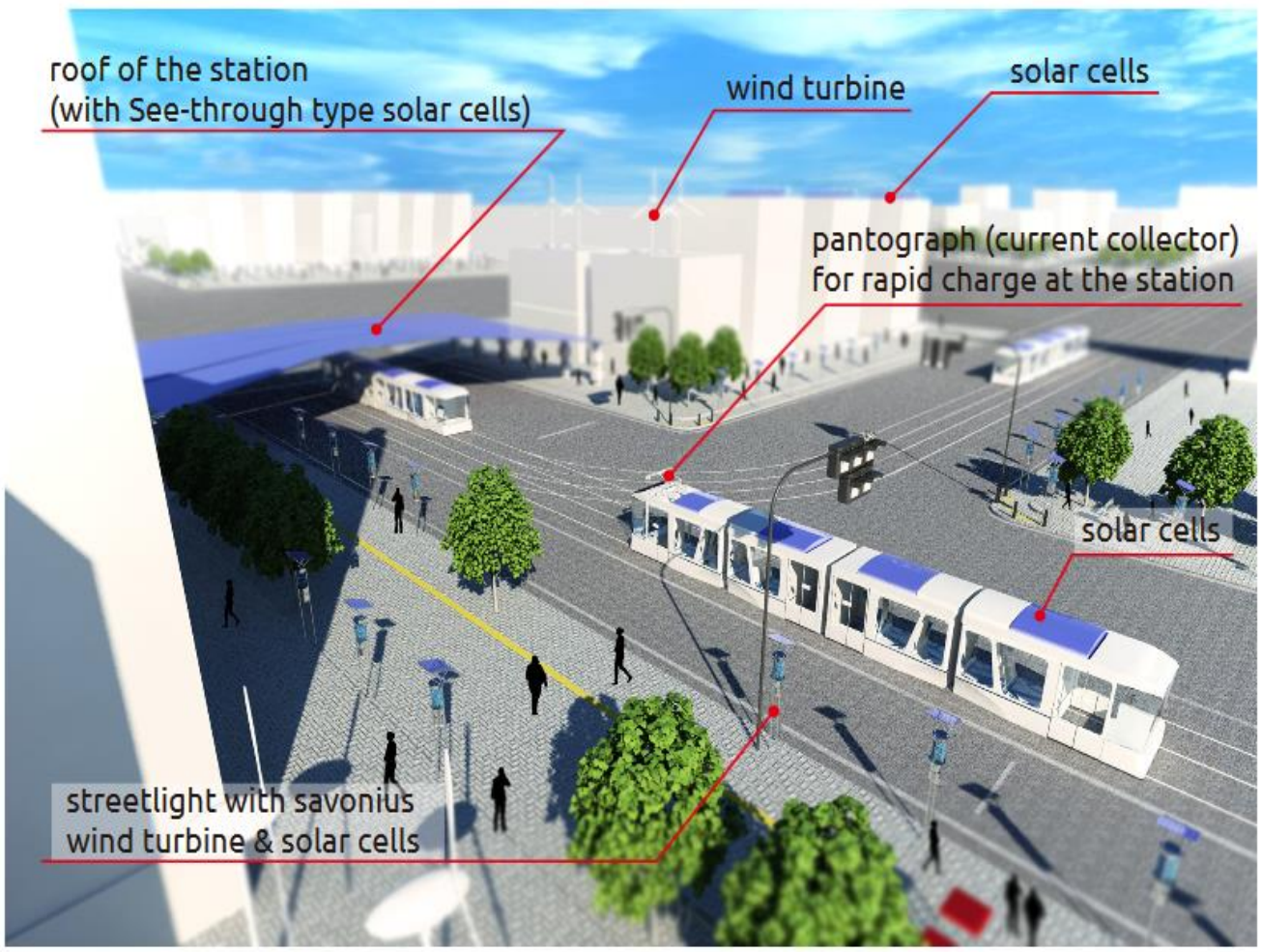

Figure 3.4: The town where the solar light rails run

3.2.3. Rapid charge

Charging time is calculated from an electric energy required to run to the next station. Charging time means stoppage time at the station. The EDLC trolley bus has already run in Shanghai (China). When EDLC of 600 V - 200 F is charged by 200 A, it takes 200 s to the full charge. Their EDLC is used in the range 400-600 V.

If we assume the voltage of EDLC to be 600V in this system and the required capacitance of EDLC is 25F, it takes 30 s when EDLC of 600V -25F is charged by 500A and 15 s when it is charged by 1,000A. Table 3.2 shows stop times at the stations and corresponding kilometer that can travel.

Table 3.2: QUICK CHARGING AT TRAM STOPS

Battery charging	Charged energy	Running distance after charging	Running distance after charging
current & duration	(at a battery terminals)	(without air conditioning)	(at the maximum air conditioning load)
1000 A - 61 s	35.6 MJ	Equivalent to 7.9 km	4.0 km or more
500 A - 196 s	56.9 MJ	Equivalent to 12.7 km	6.4 km or more

Table 3.3 shows the summarized information about Japan's solar tram project.

Table 3.3: Japan's solar tram project

Tram operation	Frequency 6 trains/h, railcars operating hours 18 h/day
A tram demand power	2.5 kWh per Km
Total demand power	270 kWh per day for a station
Required area	470 m^2 for a station

3.3. Solar LRV, economic and environmental worth

In Japan, according Table 3.4 fossil fuel power generation accounts for over 60% of all electric power [8]. This means that more fossil fuels are consumed, when electric vehicles spread.

Table 3.4: Composition of electricity generation in JAPAN (2007)

Nuclear	25.6%
Petroleum etc.	13.2%
LNG	27.4%
Coal	25.3%
Pumped-	1.0%
Hydropower	6.6%
New Energy etc.	1.0%

It is interesting that an advanced country like Japan could employed the new energies like solar one to produce just 1% of the electric power need over its country.

Some environmental impacts results of the solar energy use:

- Reduction of the emissions of the greenhouse gases(mainly CO2,NOx) and prevention of toxic gas emissions (SO2,particulates)
- Reclamation of degraded land
- Reduction of the required transmission lines of the electricity grids
- Improvement of the quality of water resources

Some socio-economic impacts of the solar energy use:

- Increase of the regional/national energy independency
- Provision of significant work opportunities
- Diversification and security of energy supply
- Support of the deregulation of energy markets
- Acceleration of the rural electrification in developing countries.

3.4. Unsolved problems

The remaining unsolved problems are:

- Energy loss

If the electric power is supplied to the railcar from the renewable energy power plants through the contact wire. However, the railcar cannot start in cloudy or rainy days even by this method. Moreover, the power transmission loss cannot be neglected. The transmission loss in Japan is about 5.6%. In 2008, not less than 45 billion kWh electric power was lost.

- Connecting wayside or farm solar panels to the rail network.

It is difficult finding appropriate farms close enough to the rail network. We also need to address the issues around safety and integration of a secondary power source and managing how and when the solar power is being sent to the rail.

Failure to address the technical challenges identified may reduce the actual generation when compared with the expected or installed capacity. The worst case could result in suboptimal operation of equipment, which can have a huge impact, and a very real associated cost, on the operation of the rail network.

- Solar energy in night times and cloudy days.

4. Estimating power demand of tramway sections

4.1. Transferring energy to railroad vehicles

Transferring energy to electrical railroad vehicles may be performed with a few different techniques. The oldest and most commonly occurring method is to use overhead catenary made of copper as phase conductor and the track as return conductor. This method is used in both tram and train electrification all over the world. The advantage is that the dangerous voltage is high up in the air, on a safe distance, and the track voltage level is low enough to be considered safe. This way, it is safe for pedestrians and cars to cross a tramway track without the risk of electrocution. The basic principle of supplying the catenary with DC voltage is shown in Figure 4.1.

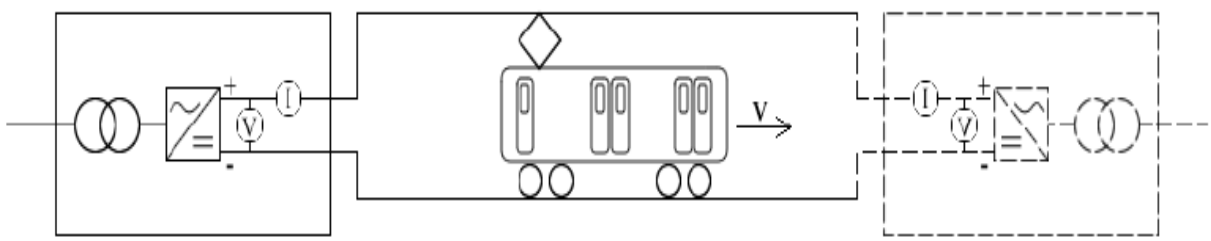

Figure 4.1: The power is transferred to the catenary from one or two rectifying stations

4.2. Calculation method

Calculating the exact power demand for one tram is not an easy task to do. There are many factors that play an important role and small adjustments may have large impacts on the total amount of power needed. The problem when calculating the power is that the main components (force, acceleration and speed) depend on each other. The resulting effort from the motors needed to overcome the resistance and accelerate the tram

$$F_{acc} = ma + R_{total}$$

Where the acceleration force is depending on mass, acceleration and the total resistive forces. The resistive forces is in turn depending on speed according to

$$R_{total} = (0{:}6wn + 20n) + bwnV + KV^2 + 20wnG$$

The used calculation method approximates the power drawn from the catenary by the tram with the mechanical output power from the motors, i.e. it is assumed that the electrical system of the tram is loss-less. The mechanical output power of the motors can be calculated with

$$P = VF_{acc}$$

The acceleration force is set by the speed controller of the tram and the available acceleration force is also depending on the speed of the vehicle. The acceleration can be found by

$$a = F_{acc} - R_{total}/m$$

And the speed of the vehicle may be determined by integrating the acceleration

$$V = \int a \, dt$$

Although the three main variables in the equations depend on each other, a unique solution may be solved by numerical simulation. By assuming that the voltage U of the catenary is constant, the current consumption of the tram can be determined as

$$I = P/U$$

An example of available tractive effort and motor power in a tram is shown as a function of speed in Figure 4.2 and as a function of time during an acceleration from 0 to 60 km/h in Figure 4.3.

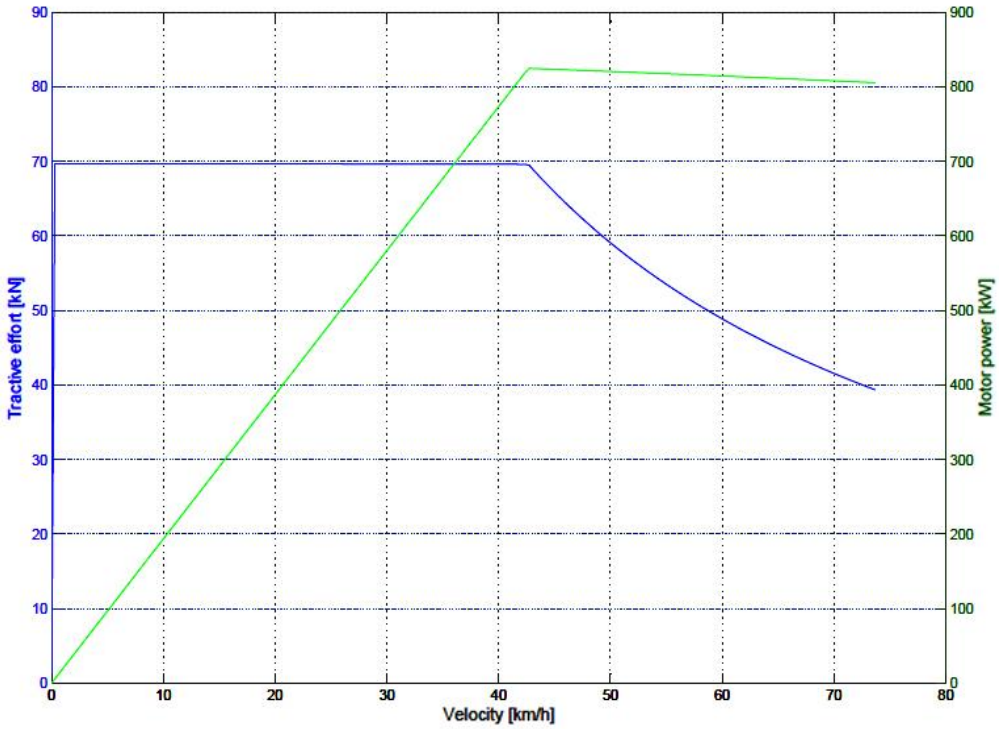

Figure 4.2: Example of tractive effort and motor power as a function of speed.

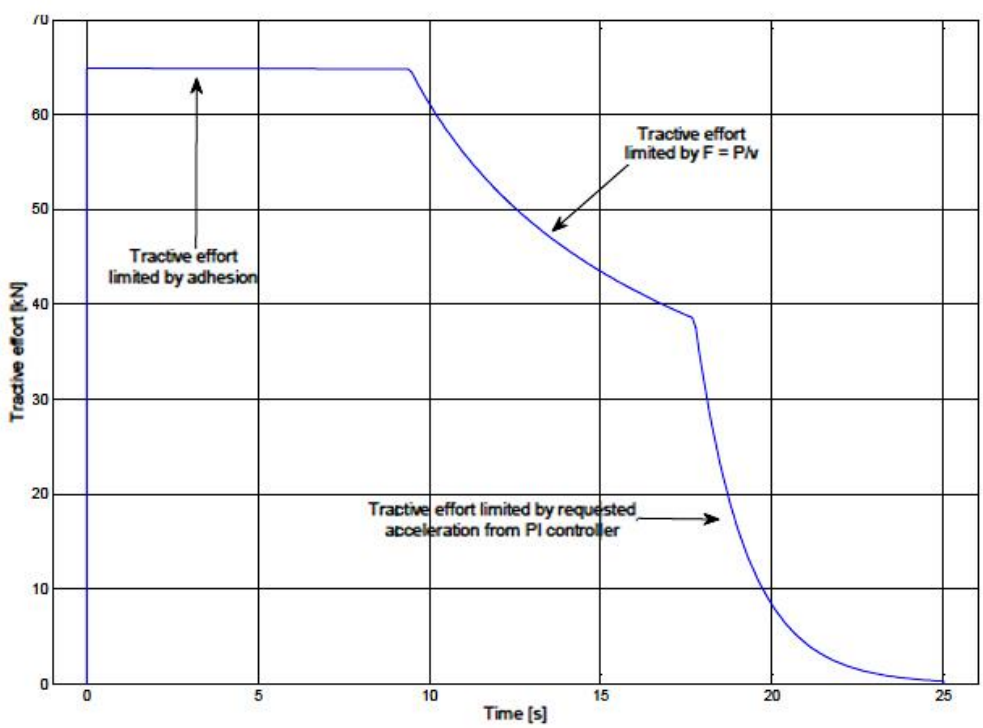

Figure 4.3: Example of tractive effort as a function of time during an acceleration

4.3. Tractive force, energy and current need during an acceleration

The current drawn by a tram may be divided into three different phases: acceleration, constant speed and idling. The largest energy consumption takes place during the acceleration phase and these peaks are the major reason for short term overloading of the rectifying stations. The current need during constant speed and idle phases are not unimportant by any means, but they are simpler to estimate with a fairly accurate result.

The measurements showed that the different tram types have different current consumption curves, which originates from how the motor controller is built. The measurements have shown that the amplitude and the shape of a current curve are typical of the accelerated tram (Figure 4.4).

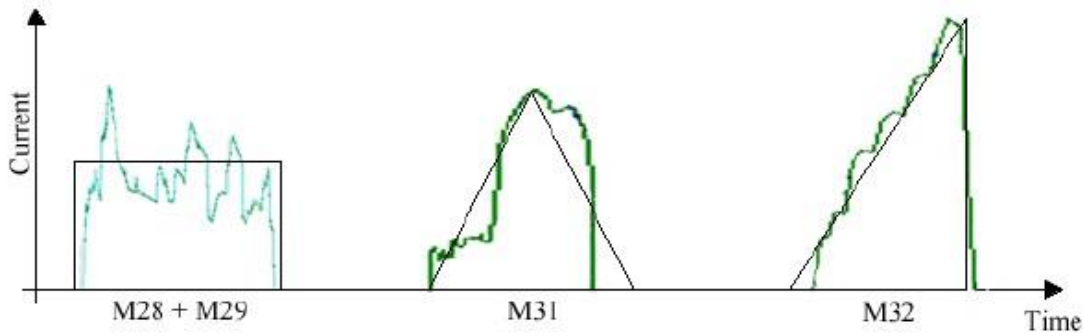

Figure 4.4: Current shape black for different tram types during an acceleration sequence

Table 4.1 shows the characteristics of M28, M29, M31 and M32 trams operating in Gothenburg, Sweden, as will see in the section 6, the characteristics of M32 tram are closely similar to Cityway tram of Rome.

Table 4.1: Current tram types in Gothenburg*, Sweden [9]*

	M28	M29	M31	M32
				
Built by	ASEA/ASJ	Hägglunds	ASEA/MGB	Ansaldobreda
Trams ordered	70	60	80	65
Number series	701-770	801-860	300-380	401-465
Delivered	1965-1967	1969-1972	1998-2002	2004-2012
Weight	16.8 ton	17.0 ton	34.5 ton	38.9 ton
Length	15.1 m	15.1 m	30.7 m	29.6 m
Sitting capacity	38	36	81	82
Standing capacity	78	82	109	104
Nominal power	176 kW	200 kW	300 kW	424 kW
Maximum speed	60 km/h	60 km/h	70 km/h	80 km/h

4.3.1. Simulink model

To achieve a solution which outputs force, energy, power and current, a simulation environment utilizing the described formulas was setup in Matlab Simulink [10]. The simulation uses a speed control built on a simple PI-controller to simulate the desired tractive effort from the driver to the motors. To show the model and compare it to measurements, a simulation was run where there first is a speed-step to increase the speed from standstill to 60 km/h and after 25 seconds a counter-step is set to brake the tram to standstill. The needed inputs to the simulation is the different parts of the resistive forces and limits for maximum acceleration, maximum tractive force and maximum power. Since the tram with highest similarity with exiting trams in Rome (like cityway 2) is in some sense most interesting, the values for a M32 tram were inserted into the model.

Figure 4.5 shows the tractive effort in kN during the run and Figure 4.6 shows speed and distance covered during the run. The result from these figures is as expected and very similar to figures from the technical specification for the M32 tram.

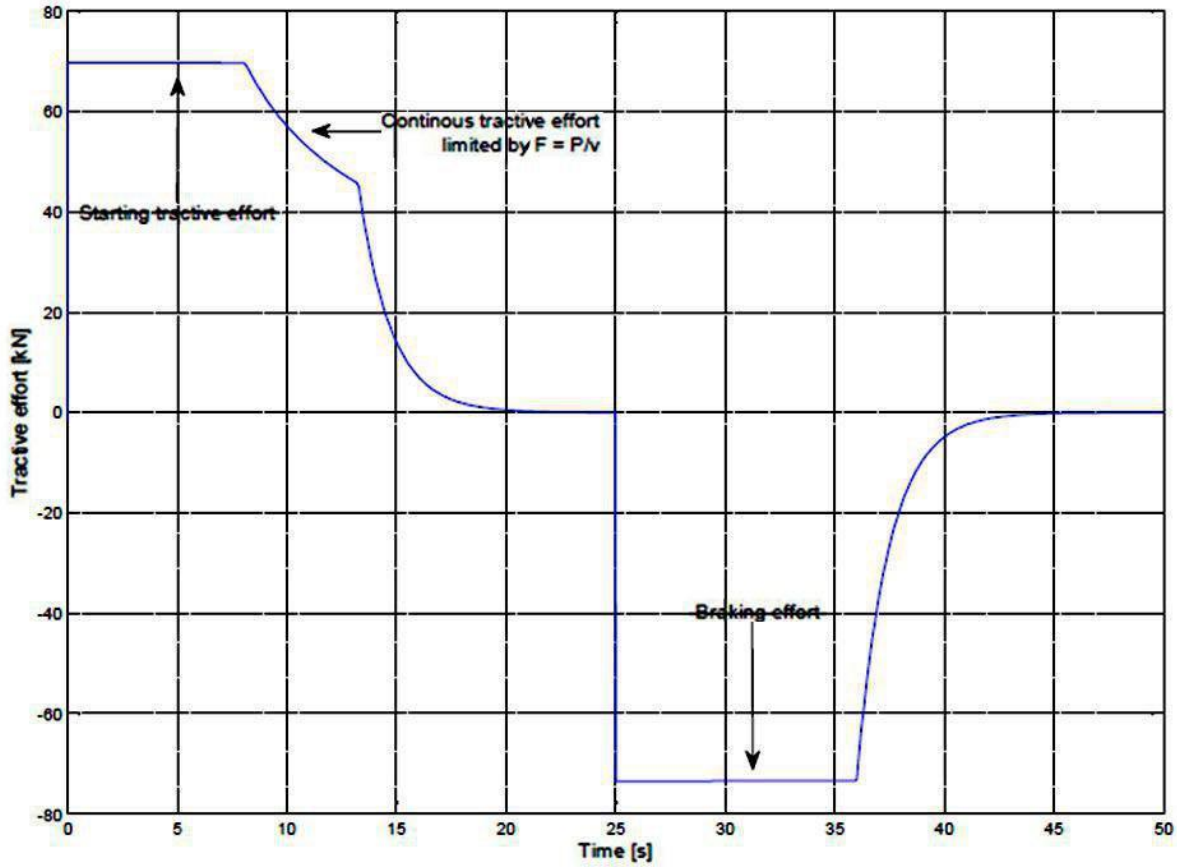

Figure 4.5: Simulation of tractive effort for a M32 tram.

As shown in Figure 4.5 at the constant speed and braking phases the tractive effort is negative which means during the brake potential energy releases in the form of thermal and kinematic energy. According to the Figure, area blow the curve of braking phase (released energy) is about 40% of area under the acceleration curve, so we can storage this energy by the onboard battery to repower tram at the acceleration phase. This subject will be described completely in the section 9.

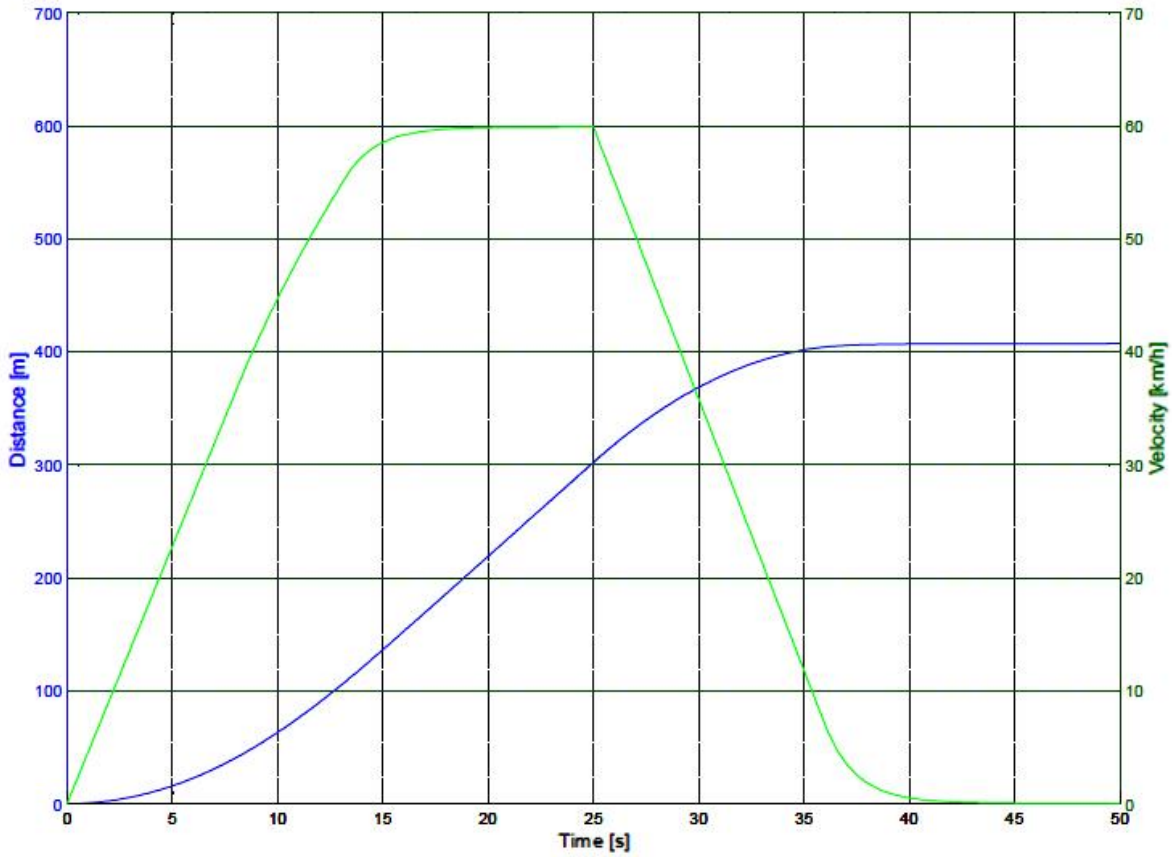

Figure 4.6: Speed and distance plot of a M32 tram simulation.

The simulation also outputs power and current curves and the total amount of energy needed during one acceleration. These figures and results are presented in Figures 4.7 and 4.8 and Table 4.2

4.3.2. Simplified model

To be able to calculate the power and current demand on a section with several trams in movement simultaneously, it is necessary to simplify the Simulink model.

The simplified model is based on the simulation with numerical iterations in computer software. The major difference is that the force is considered to be constant for the entire acceleration, which also gives a constant acceleration and linearly increasing speed. These approximations are built on the observation that the current increases almost linearly during the first part of an acceleration. This leads to a somewhat higher current peak and must therefore be compensated by reducing the acceleration somewhat to compensate for the fact that the acceleration is limited by the available power during higher speed. Figure … shows a comparison of a recorded current peak during an acceleration with a M32 tram on a flat track and the corresponding current peak output from the Simulink model and the simplified model. The Simulink model fits the recorded data quite well, both in magnitude and shape, and the simplified model has a somewhat higher amplitude. Figure … shows a similar situation as in Figure … but the recorded data comes from a M32 tram running up a 40‰ slope. Both the current from the Simulink model and the simplified model have slightly higher amplitudes than the recorded data and the shapes of the simulated curves are somewhat deviating from the recorded data.

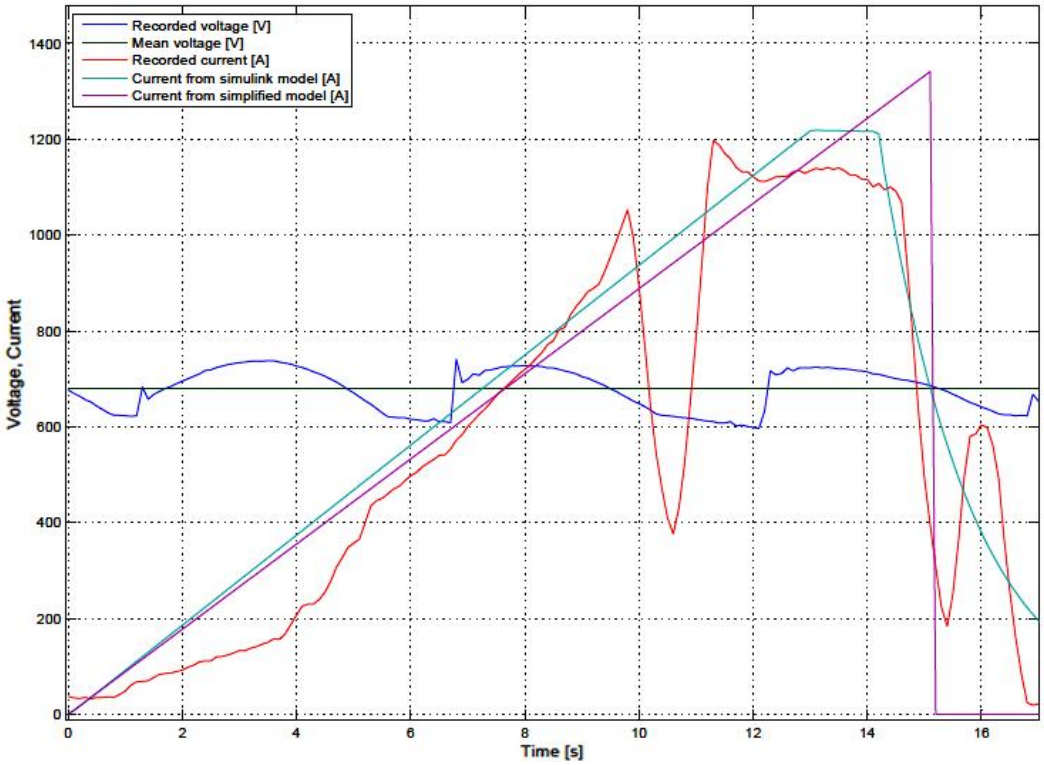

Figure 4.7: Voltage and current plot from a M32 tram acceleration on a flat track.

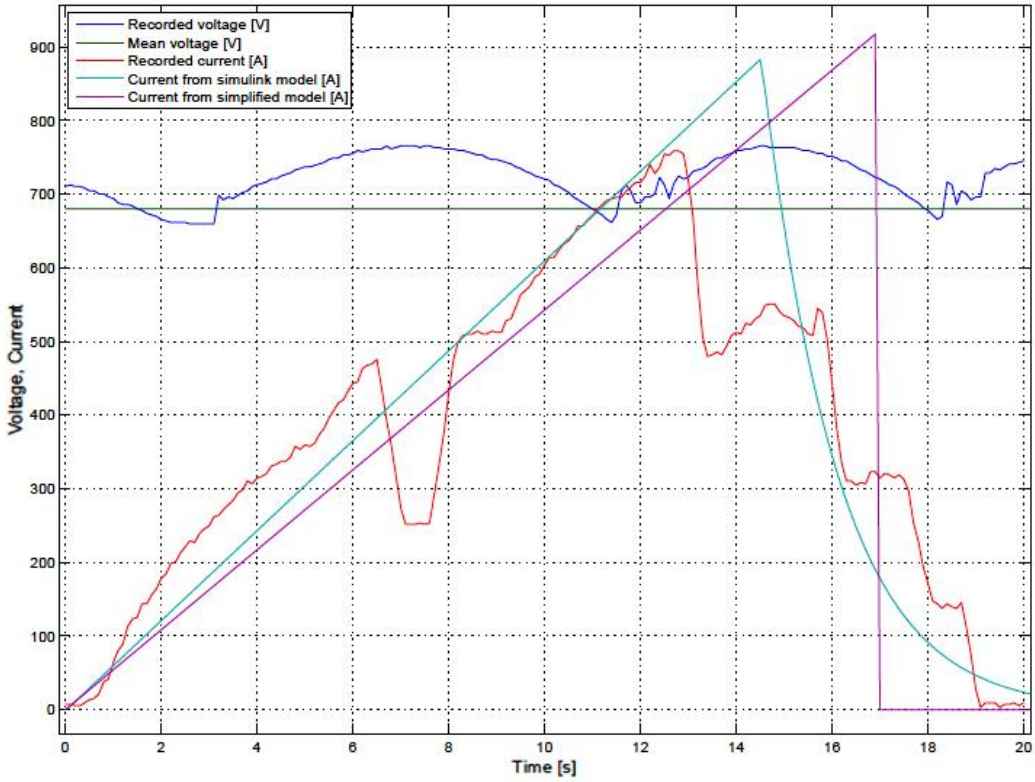

Figure 4.8: Voltage and current plot from a M32 tram acceleration in a slope of about 40 ‰

Table 4.2: Energy usage from measured data, Simulink model and simplified model.

Slope	Recorded data	Simulink model	Simplified model
0 ‰	6.52 MJ	6.87 MJ	6.77 MJ
40 ‰	5.48 MJ	5.27 MJ	5.30 MJ

To determine the accuracy of the two models, the total amount of energy used during the acceleration may also be compared. The energy from the recorded data is found from integrating the product of voltage and current:

$$W = \int P = \int UI$$

The energy from the Simulink model is generated automatically during the simulation and the energy from the simplified model is also found from integrating the product of voltage and current. The voltage is here estimated as the average voltage from the measurements and is equal to 680 V. The result of the comparison is found in Table 4.2. The table shows that both models are accurate enough and the acceleration sequence is therefore hereafter modelled with the simplified model. One may also notice that the energy use climbing the slope is lower than the energy use during the acceleration on the flat track. This is because the speed on the flat track is about 50 % higher compared to the speed during the climb.

4.4. Resistive forces and current need during constant speed

As trams travel in constant speed, the resistive forces from air drag and track are the ones that need to be overcome. As these forces are constant at constant speed and constant slope, they may be estimated by a constant current. The resistive forces on a flat track are relatively low in speeds up to 100 km/h but it increase fast if the slope increases. By analyzing the current shapes of the recorded data, it was found that the driving cycles of the trams mostly consists of accelerations and decelerations. After an acceleration, it is common that the tram runs on only idling current since the speed barely decreases by the low resistive forces. The effect of this is that constant speed current may be approximated with only idling current. A problem with this approximation is that when a tram enter a slope, the current needed to compensate for the increased resistance will not be accounted for. This may be compensated for by raising the idling current or by introducing one extra acceleration when simulating a section with a slope.

4.5. Current need during idling

As trams stand still at stops and in turning loops, the systems onboard the tram draws an idle current which may be seen as constant. The measurements showed that the idle current from a M32 tram draws about 60 A in idling current. To run a simulation with other tram types, the idle current must be measured, taken from the specification or estimated by comparing to known values. Even though the idle current may seem as a small quantity in contrast to the acceleration current, it must be taken into consideration, especially as it is not uncommon for several trams to stand at a turning loop at the same time.

4.6. Simulating the tram path

With input values such as the mix of different trams, number of passengers on each tram, number of stops on the section and tram frequenting, a simple result for power demand estimation may be found. The problem with this simple setup is that the trams are not always exactly on time. The insecurity factor is very important as the number of trams on the investigated section may be heavily over frequented due to previous stops and delays. As the power demand for trams arises mostly during accelerations, it is important to know how many tram stops and traffic lights there are on the investigated section. Together with the rest of the parameters, such as passenger count, speed, slope and rolling resistance it is possible to estimate how much energy that each acceleration requires and thereby, total energy per time unit may be found. We will argue about tram line 8 in Rome and power need consideration in section 8.

5. Estimating power production from the solar panels

5.1. Production process

Producing solar energy is harnessing the sun's rays or photons and converting them into electrical energy. This is done through solar panels composed of PV cells installed. When the sun hits a cell, the photons are converted to electrons of direct current (DC) electricity that flow through an inverter where they are transformed into an alternating current (AC) power. Electricity produced from solar panels is then ready to be used.

Solar energy produced is tracked by an energy meter. Any unused electricity simultaneously can go back into the electrical network. At night or on cloudy days, when the production is less than needed, the network supplies the users.

The amount of produced electricity depends on the size of the panel, the efficiency of the solar cells and the amount of sunlight the panel gets.

Because the seasons and weather conditions affect the amount of sunlight hitting the cells and the amount of sunlight is also variable, you can't use just the solar panel ratings to predict the production.

5.2. Dimension of solar panels

Nowadays, a typical silicon PV panel is about 39 x 65 inches (1.00 x 1.65 m). It is divided into 60 little squares, the individual solar cells, linked each other by wires. The cells are where electricity is produced and the wires carry the electricity to a junction box where the panel is hooked into a larger array.

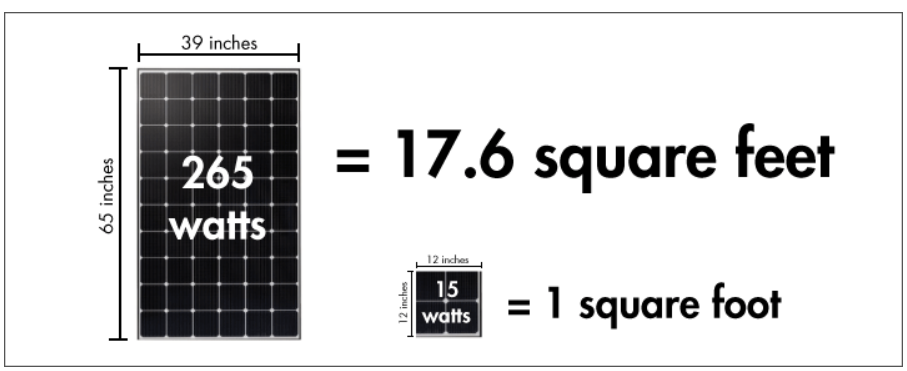

Figure 5.1: A typical solar panel size

The more cells are working together, the more power they create. Therefore, the size of the panel is relevant to calculate how much electricity a panel is producing. Solar panels dimensions are almost fixed but they became progressively improving their efficiency.

5.3. Weigh of solar panels

Understanding how much solar panels weigh is crucial if you're planning on installing a rooftop solar system. Knowing a solar panel's weight is the best way to be certain that your roof can support a full installation.

We reviewed product specifications for the top 10 solar panel brands most frequently and compared the weight of their standard 60-cell residential solar panels in Table 5.1. While there is some variation from brand to brand, most panels weigh somewhere in the neighborhood of 40 pounds (almost 18 kg) which we will assume 20 kg in the calculation part.

Table 5.1: The weight of common solar panels [11]

Solar Panel Manufacturers	Solar Panel Weight (60-Cell Residential Panels)
SolarWorld	40 – 47 lbs
LG	38 lbs
Canadian Solar	40 – 51 lbs
Hyundai	38 – 41 lbs
Hanwha SolarOne	40 – 42 lbs
Hanwha Q CELLS	41 lbs
Trina	41 – 50 lbs
SunPower	33 – 41 lbs
Axitec	39 – 41 lbs
Kyocera	42 – 44 lbs

5.4. Efficiency of solar panels

Solar efficiency relates to the amount of energy available from the sun to be converted into electricity. Back in the 1950s, the first solar cells were capable of taking 6% of the energy from the sun and converting them into electricity.

An array of 60 cells you see in figure 5.1 would have produced an electric power of about 20 W just enough to light up a very small incandescent bulb. The efficiency progressively increased to convert 15% in 2012 and nearly 20% nowadays.

By combining the efficiency of the cells with the size of the panel, you get a number called the “power rating.”

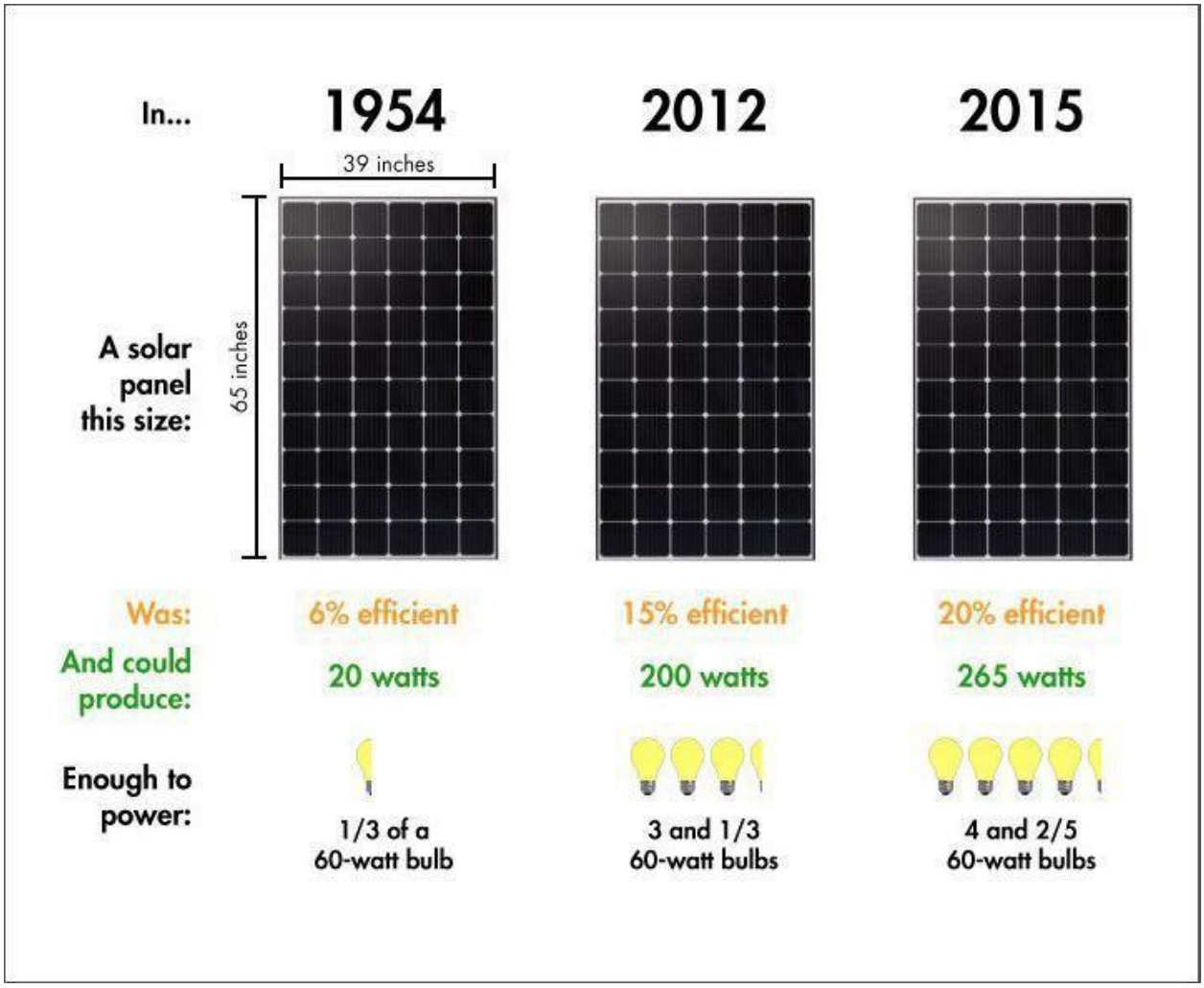

Figure 5.2: solar panel efficiency [12]

5.5. Power rating for an average solar panel

Nowadays, a typical solar panel produces an average of 265 W, variable according to size and efficiency until 320 W.

To determine a Standard Test Condition (STC) rating, solar labs test the panels under ideal conditions called “peak sun” corresponding to 1000 W of sunlight per square meter of surface. That’s approximately equal to the power of the sun at noon, on a sunny day, at the equator.

For example if on the back of a panel the label shows a STC rating of 250 W for the panel: should this panel receive full sun for one hour, it would produce 250 Wh of electricity (1 kWh in 4 hours).

So we consider a typical solar panel to install on the rooftop of the tram as one energy source with characteristics reported in Table 5.2.

Table 5.2: Employed solar panel properties

Dimension	1.65 m (L) × 0.99 m (W)
Area	1.63 m2
efficiency	20%
power rating	260 W
weight	20 kg

6. Trams in Rome

The urban tramway network of Rome is made up of six lines, 192 stations and 164 vehicles for a total length of about 31 km. The current Rome tram system is a leftover from what once was the largest tram system in Italy. With its fragmented structure, it does not currently function as a backbone of the city's public transport. The system is owned and operated by *Agenzia per i Trasporti Autoferrotranviari del Comune di Roma* (ATAC SpA).

6.1. Trams currently in use

6.1.1. ATAC Series 7000

In 1940 the public transport company ATAG commissioned the Mechanical Workshops of Stanga in Padua to build an articulated prototype tram. The prototype, delivered in 1942 and numbered 7001, operated briefly and was destroyed in the bombing of Rome on July 19, 1943. The order was confirmed, however, and the delivery of 50 cars occurred between 1948 and 1949 (figure 6.1).

These cars, which have undergone an operation for modernization in the 1980s, are still in operation in Rome, with the only exception of two of them, recently scrapped. Moreover, one car has been transformed into *Ristotram* (restaurant car).

A further order of eight similar trams was made in 1953. These were later modernized by ATAC at the Viberti workshops.

6.1.2. SOCIMI T8000

33 articulated double-ended low-floor tramcars were delivered in 1990 and 1991 by SOCIMI in Milan (figure 6.2). These trams are fitted with a 2-axle bogie at both front ends and small wheels in the center of the car, thus allowing a 70% low floor. Since SOCIMI went broke, 27 of the 60 cars on order were not built at the time, but in 2003 and 2004 eight additional cars entered into service, assembled from spare parts salvaged from the dissolved SOCIMI works.

Figure 6.1: ATAC Stanga Class 7000 series tram no. 7027

Figure 6.2: SOCIMI T8000

6.1.3. Cityway I

These double-articulated trams were ordered from Cityway Fiat Railway in 1998 to mark the opening of line 8 (figure 6.3). The 70% of its length is low-floor; raised floor sections are located at the ends. The entire train measures 31 meters. One innovation introduced was the air conditioning system. Currently they are in regular operation on lines 2 and 8. Table 6.1 shows the characteristics of Cityway I tram [13].

Table 6.1: Cityway I characteristics

Identifying numbers	9101-9128
Construction years	1998- 2000
Constructor	Fiat Ferroviaria (Alstom) - Elettromeccanica Parizzi
Axle configuration	Bo-2-2-Bo
Width	2400 mm
Total length	31250 mm
Chassis height excluding pantograph	3300 mm
Catenary tension	600 V CC
Maximum rim power	732 kW
Maximum speed	70 Km/h
Empty weight	40 t
Weight with normal load	53.5 t
Total Seats	54
Standing	136
Floor height	350 mm (390 mm over the bogies)
Minimum curvature in line	18 m
Trolley step	1750 mm
New wheel diameter	680 mm
Brakes	Rheostat electric and stopping solenoid plus two trolley shoes

Figure 6.3: Cityway I tram in Rome

6.1.4. Cityway II

In 1999, other 52 articulated trams were ordered from Fiat-Alstom, following the new trend of with three suspended sections (figure 6.4). The length is 33 meters. The prototypes cars, which never entered into service, had additional articulated sections, forming a vehicle of 41.45 meters in length, with 9 sections and 5 carriages. These trams are used only for line 8.

The characteristics of Cityway II are shown in the Table 6.2 [14].

A low-floor tram has no stair steps between one or more entrances and part or all of the passenger cabins. The low-floor design improves the accessibility of the tram for the public and also may provide larger windows and more airspace. An accessible platform-level floor in a tram can be achieved either by using a high-floor vehicle serving high-platform tram stops, or with a true low-floor vehicle interfacing with curb level stops.

Table 6.2: Cityway II characteristics

Identifying numbers	9201-9252
Years of construction	1999-2004
Constructors	Fiat Ferroviaria (Alstom)
Axle configuration	Bo-2-2-Bo
Width	2400 mm
Total length	33000 mm
Engine power	4×178 kW
Max speed	70 Km/h
Empty weight	40 t
Total Seats	56
Standing	184
Low floor	100%
Axles	8
Doors	4

Figure 6.4: Cityway II tram in Rome

7. Climate situation in Rome

7.1. Average temperature

Rome and its metropolitan area has a Mediterranean climate with cool winters and warm to hot summers. According to *Troll-Paffen* climate classification, Rome has a warm-temperate subtropical climate. As shown in Table 7.1 and Figure 7.1, Rome has a relatively high average temperature, around 16˚c.

Table 7.1: Average Temperature in different months in Rome

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
°C	8	9	12	14	21	23	26	24	22	18	13	10
°F	46	48	54	57	70	73	79	75	72	64	55	50

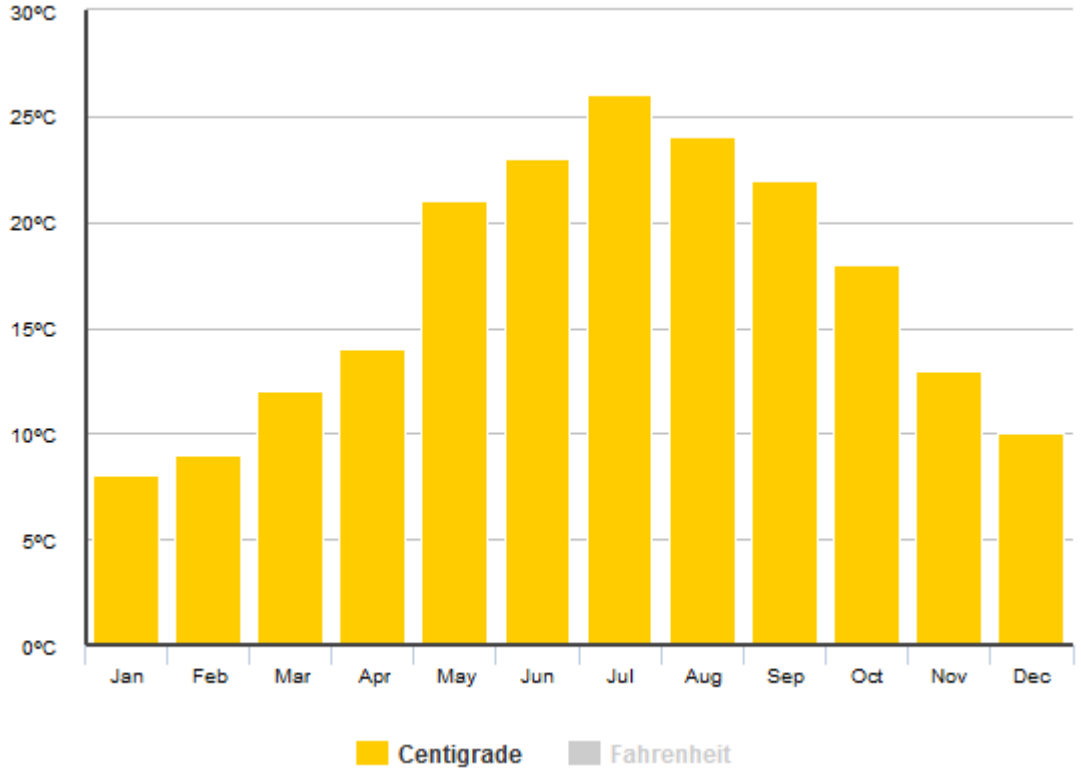

Figure 7.1: Average Temperature in different months in Rome

7.2. Average daily sunshine times

Rome enjoys one of the highest number of hours of daylight in Europe. Days in winter are not as short as in the northern part of the continent, the average hours of daylight in December, January and February is 10 hours (for comparison in London, Moscow and Warsaw is about 8 hours). Table 7.2 shows the hours of light in different months in Rome [15].

Table 7.2: Hours of light in different months in Rome

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
hours of light	10	11	12	13	15	15	15	14	12	11	10	9

Table 7.2 and figure 7.3 show the average daily sunshine times, which are efficiently important in solar panels function.

Table 7.3: Average Daily Sunshine Hours

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hours	4	5	7	7	9	9	11	10	8	6	4	3

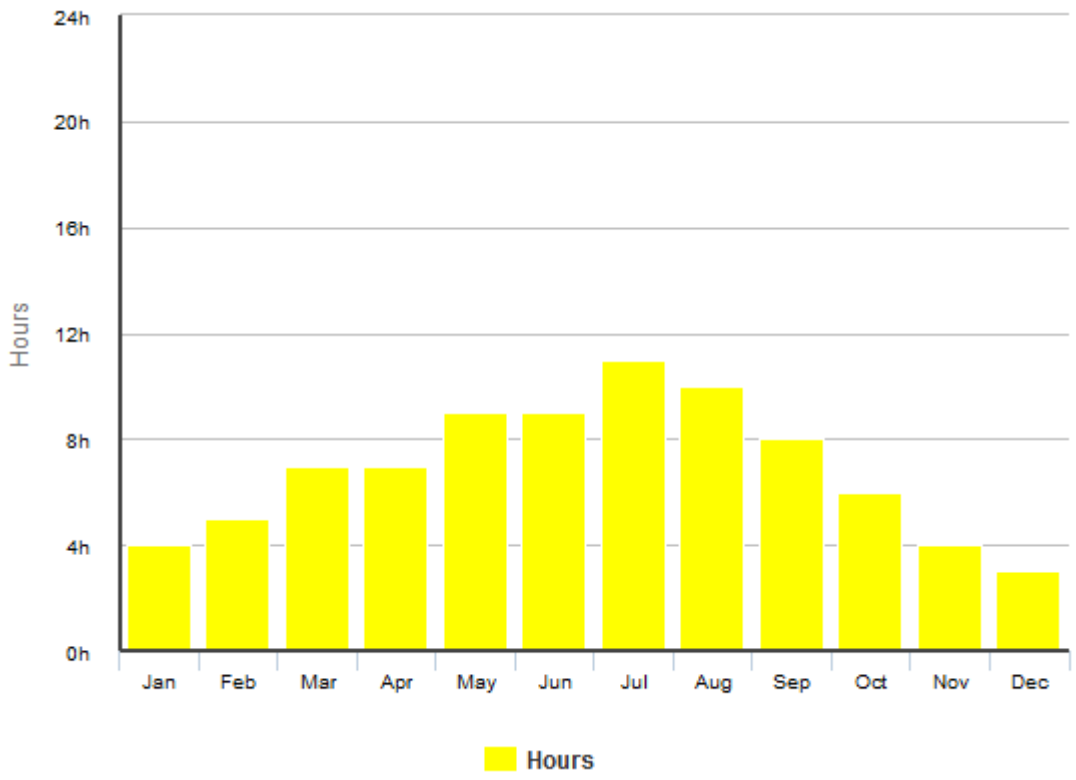

Figure 7.2: Average Daily Sunshine Times

7.3. Average rainy days

Rome is conferred on average 837.3 mm (33 in) of rainfall per year, or 69.8 mm (2.8 in) per month [16]. On average there are 83 days per year with more than 0.1 mm (0.004 in) of rainfall (precipitation) or 6.9 days with a quantity of rain, sleet, snow etc. per month. In Figure 7.3 and Table 7.4 can be shown average rainy days during a year.

Table 7.4: Average rainy days and rainfall

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mm	25	20	19	18	33	6	7	0	42	38	49	96
Days	7	6	7	9	7	4	3	0	6	8	8	9

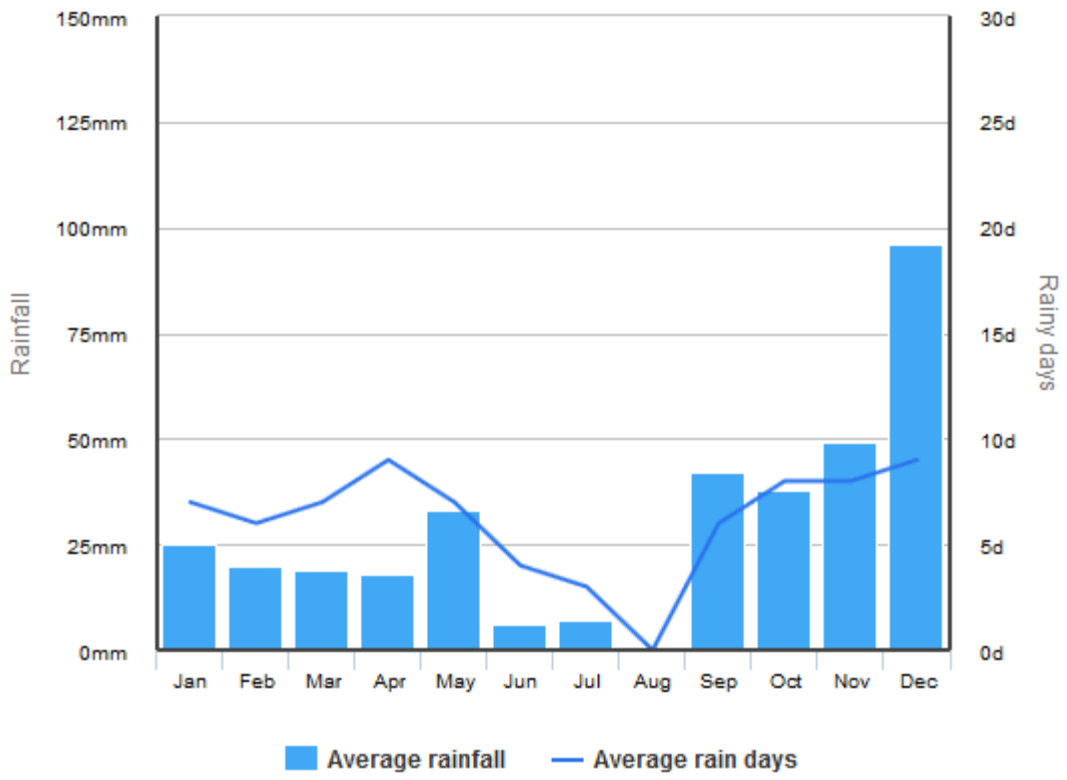

Figure 7.3: Average rainy days and rainfall

According to the elevate number of sunny days (on average 282 days in year) and daylight hours, Rome has a great potential to the solar energy use. Due to the high demand from the population and the touristic public transport users, it could be successfully employed this type of energy especially in this sector, which is one of the most important fossil fuels and natural source consumer.

In not solar countries, like Japan, it can be used just 1100 hours/year of sunshine for power generation through solar cells, while this numbers in Rome, according to the following calculation, is 2525 hours/year, which is 2.3 times more than Japan.

$$\textit{Annual sunshine hours} = \textit{Average Daily Sunshine Hours} \times 365 = (4+5+7+7+9+9+11+10+8+6+4+3)/12 \times 365 = 2525 \textit{ hours}$$

8. Solar-powered trams

In cities like Rome, where tram lines are already equipped with catenary, it would be rational using the available equipment at night times and on not sunny days rather than removing the whole electrical systems and constructing expensive new structures, like solar canopies or solar rail side panels or charger stations.

As a sample, we will consider the line 8 of the tram network system in Rome to study the possibility of power generation from solar photovoltaic panels mounted on the roof of the trams.

8.1. Feasibility of panels positioning on the roof

The total area of the roof of a Cityway 2 tram which operates on line 8 can be obtained as follows, basing on its dimensions reported in Table 6.2.

$$\textit{Total area of the roof} = 33\ m \times 2.4\ m = 79.2\ m^2$$

The area of a 60 cells solar panel can also be calculated as follows basing on data from figure 5.1.

$$\textit{Area of one solar panel} = 1.65\ m \times 0.99\ m = 1.63\ m^2$$

$$\textit{Number of solar panels} = 79.2 / 1.63 = 48$$

Taking into account the potential maximum distribution of the panels on the roof, according to Figure 8.1 it would possible to position about 40 solar panels, 20 panels longitudinally (20 x 1.65 m = 33 m) x 2 panels transversally (0.99 m x 2 = 1.98 m < 2.40 m).

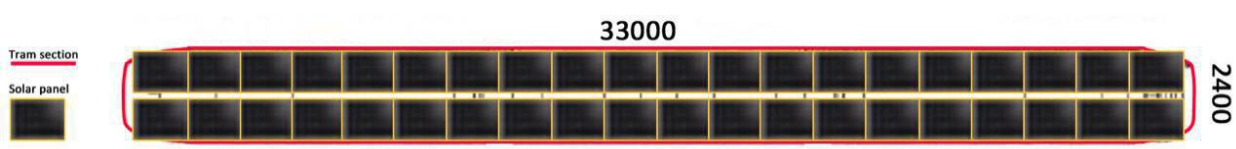

Figure 8.1: Solar panels positions on the rooftop

Nonetheless, the total area of the roof is not available because of the pantograph spot and other equipment; therefore we can estimate 75% of the total area available to install a maximum of 30 panels.

In order to ensure minimal risk of structural failure for rooftops, the maximum allowable loading on it is rated at 97.6 kg/m^2. A safety factor of 4 was also considered for this application to minimize the potential risk of structural failure due to unexpected loads, such as wind, captured water, hail stones from rain or even animals such as birds.

Basing on that, the allowed load on the roof would be 97.6/4 = 24.4 kg/m^2.

Since a solar panel with 1.65 m^2 area weights about 20 kg (Table 5.1), the maximum load of panels is 20 kg /1.65 m^2 = 12.1 < 24.4 kg/m^2.

Therefore, we don't have any problem with overloading from panels.

8.2. Line 8

In the past, Rome had the largest tramways network in Italy, but, in the second part of 20th century, like many other cities, ripped up tracks and replaced most of its tram lines with exhaust-spewing buses.

A few of the old lines are still in service, moreover, as in many European cities, new lines have been added in recent years.

Line 8 is the newest line of the system, always running with modern stock and connecting the historic city center (piazza Venezia) to the West, with Trastevere railway station and via del Casaletto.

The main features of the line are summarized here below [17].

- Line opening: 23/03/1998;
- Terminus: Casaletto - piazza Venezia;
- Operating times: Sunday to Thursday 5:10 - 24:00, Friday to Saturday 5:10 - 3:00;
- Daily trips: almost 450 departures, every 5 min;
- Line length: 5450 m;
- Seat type: protected;
- Total stops: 15 per direction;
- Commercial speed: 12 km/h;
- Daily Vehicles at service per day: 18;
- Tram type: Fiat Alstom Roma2;
- Tram length: 33 m;
- Passengers capacity: 54 seated, 225 standing;
- Passengers x Km / year offered on the line: 270 million;

8.3. Calculation of power need of line 8 vehicles

According to the commercial speed and the distance between the 2 terminuses, it can be estimated the travel time for a round trip by assuming 5 min stop time at each terminus:

One way travel time = 5.45 km / 12 km/h x 60 = 27.25 min ≈ 28 min

Roundtrip travel time = 2 × 28 min + 2 × 5 min (stop time at the terminus) = 66 min

Since total trips per day are 450 departures from both terminuses, it means 225 roundtrips. Considering an operational fleet of 18 vehicles, they should travel 225/18 = 12.5 roundtrips.

As mentioned in section 4 and according to Table 4.2, the recorded data of the required power during an acceleration with 0‰ slope for a 32M tram is equal to 6.52 MJ or 1.8 kWh, also with a view to Figure 4.6, the covered distance during an acceleration is about 450 meters. As a result if we presume that tram for traveling 1 kilometer be always on accelerating then it needs 4 kWh energy per kilometer but whereof the assumption is absolutely not realistic and as we know the tram on line 8 never reach to maximum speed (70 km/h), 4 kWh for needed power is too high. Considering the distances between stops which is about 400 meters, during one kilometer we should take into account the constant speed, idling phase and stop time for boarding and alighting passengers. So assuming the power need of 2.5 kWh /km, according to the experiences in Japan, we can calculate the power need per day:

Power need of one tram for one roundtrip = 2.5 × 2 × 5.45 = 27.25 kWh

Daily power need of one tram = 27.25 × 12.5 = 340.63 kWh

8.4. Calculation of power generated by solar panels mounted on the roof

As described earlier, a solar panel in sunshine periods can normally generate 260 W of power. By assuming 30 solar panels mounted on the rooftop, the power generation for a tram operating on line 8 will be:

Power generated by 30 panels = 30 × 260 = 7800 W = 7.8 kW

8.4.1. Monthly need estimation

Due to the relevant seasonal differences, it is necessary to carry the need coverage analysis on monthly basis (Table 8.1) to compare power generated by solar panels and total power need of the tram.

Table 8.1: Power generation from solar panels in different months

Month	Sunshine period [h]	Power generated by solar panels [kWh]	Total power need [kWh]	Coverage of energy need [%]
Jan	4	31.2	340.6	9.2
Feb	5	39.0	340.6	11.4
Mar	7	54.6	340.6	16.0
Apr	7	54.6	340.6	16.0
May	9	70.2	340.6	20.6
Jun	9	70.2	340.6	20.6
Jul	11	85.8	340.6	25.2
Aug	10	78.0	340.6	22.9
Set	8	62.4	340.6	18.3
Oct	6	46.8	340.6	13.7
Nov	4	31.2	340.6	9.2
Dec	3	23.4	340.6	6.9

As shown in the table, we can provide up to 25% of the power need in July just by solar energy, on the other side, from November to January (less than 10% of need coverage) the function of the solar panels is marginal.

8.4.2. Yearly need estimation

On yearly basis, the daily average sunshine is about 7 hours per day, which allows finding out an average coverage of 16% of power need just by mounting the solar panels on the rooftops whereas this number could be improved employing integrating methodologies, which will be later described.

The following calculations are finally highlighting the relevance of the 16% energy need coverage.

Total daily power need of line 8 = 18 vehicles × 340.63 kWh = 6131.25 kWh

Total power generation by solar energy of line 8 per day = 6131.25 × 0.16 = 981 kWh

Total power generation by solar energy of line 8 per year = 981 × 365 = 358,065 kWh

9. Battery-powered system

9.1. Vehicles with onboard energy storage capability

For a better energy management of railway vehicles, there is also the possibility to equip the vehicles with an energy storage system, such as rechargeable batteries, electric double layer capacitors (EDLC), fuel cells or flywheels.

Onboard energy storage system can provide up to 30% energy saving effects by restoring regenerative energy during braking. In addition, rapid development of the onboard energy storage system enables catenary-free operation of emerging railway vehicles.

Therefore, many railway industries have recently developed energy efficient Light Rail Vehicle (LRV) with onboard energy storage system.

The various catenary-free LRVs are summarized as follows.

- *Primove by Bombardier*

Bombardier has recently developed the *Primove* system (figure 9.1) that enables its *Flexity* tram to operate catenary-free including on contactless power transfer buried in the ground. Its electric supply components are invisible, hidden under the vehicle and beneath the track. The *Primove* system uses the MITRAC energy saver that stores the energy released each time a vehicle brakes and improves the efficiency of operational energy consumption with the ultra-capacitor-based storage unit. The *Primove* system also provides energy management control system that integrates energy awareness, efficiency and carbon control into operators' business [18].

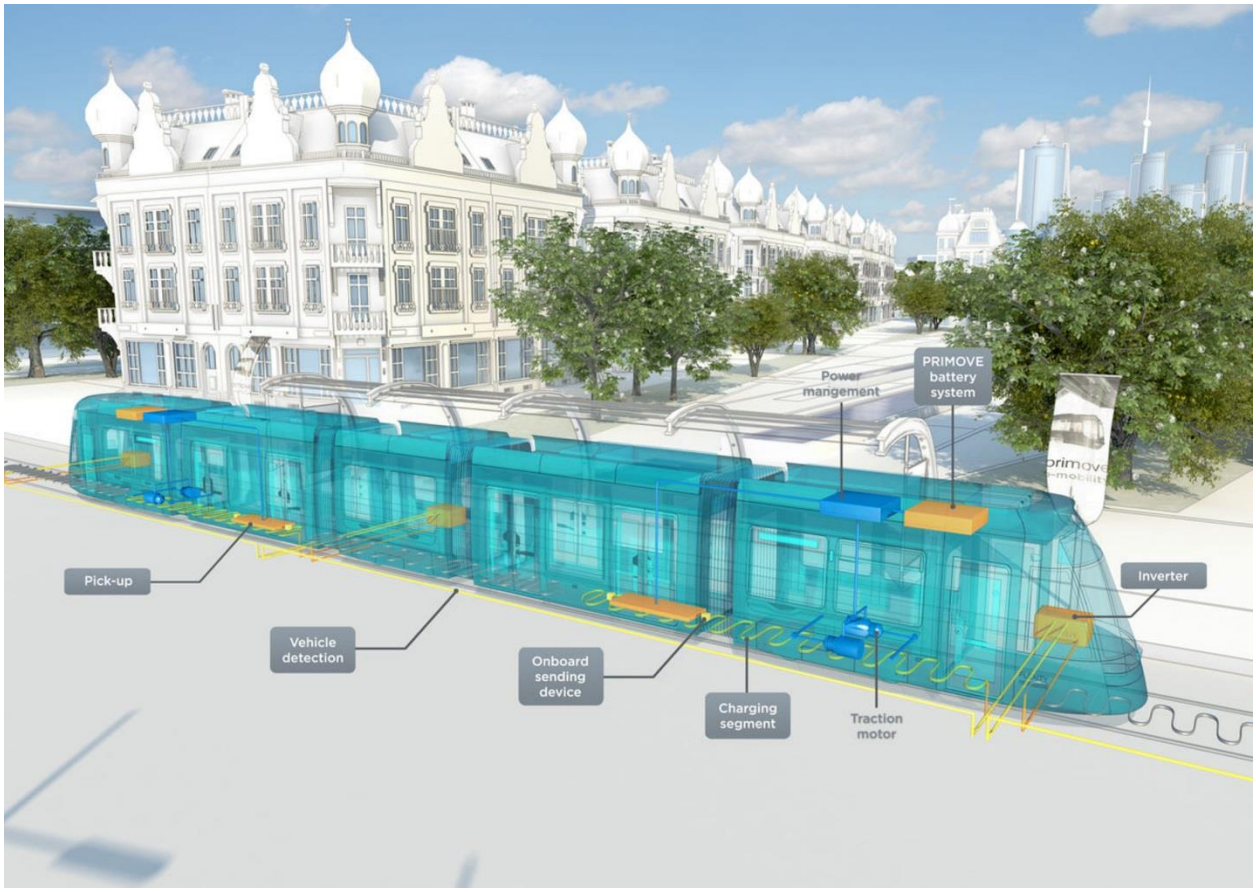

Figure 9.1: Bombardier Primove system

- *APS by Alstom*

Alstom has applied a ground-level power-supply system (APS), a third rail embedded among the tracks, for their *Citadis* trams (figure 9.2). The APS ground-level power supply system allows trams to travel without catenary and integrate harmoniously into the urban landscape. However, the main concerns of this system is to preserve the urban environment and the region's historical heritage, but not to focusing improving energy efficiency. Moreover, the APS is more expensive than a catenary-based powering system [19]. Alstom also applied their battery-powered LRV to the Citadis series and started its operation in 2007 in Nice.

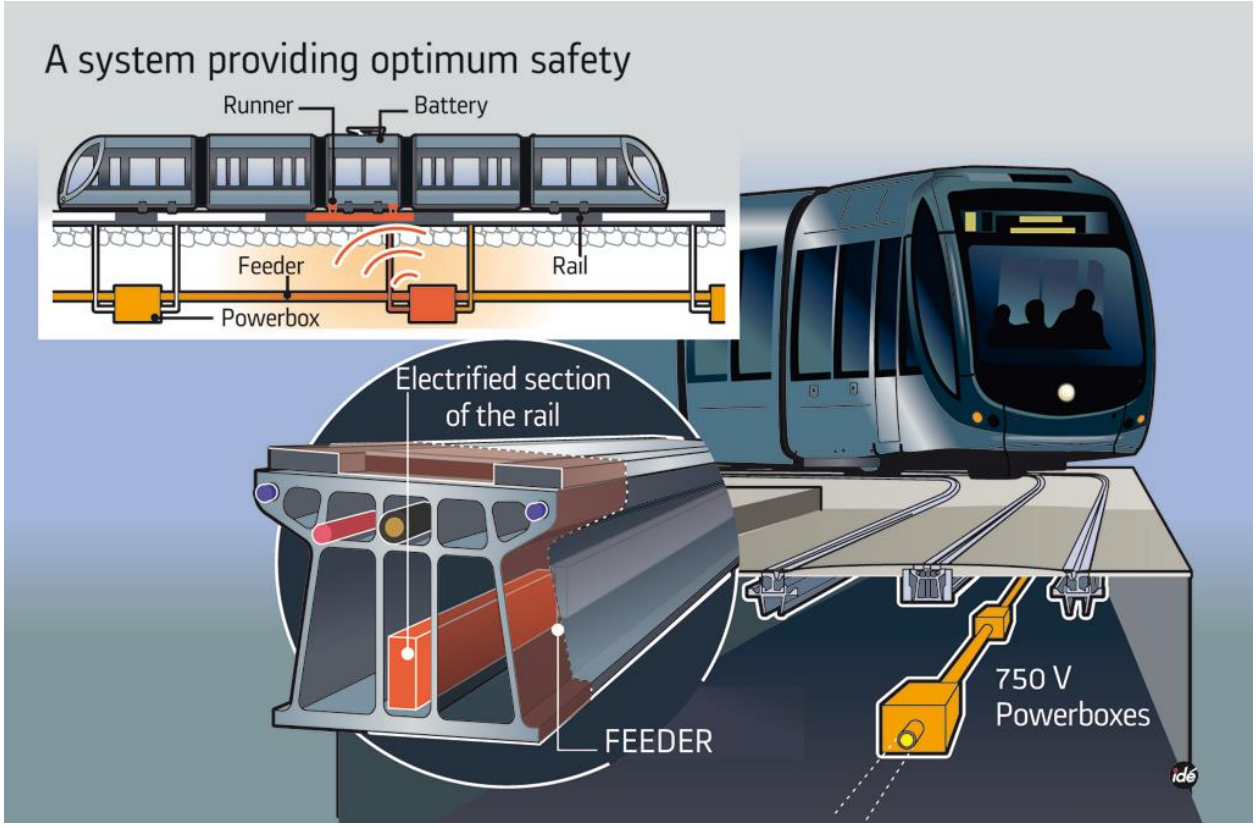

Figure 9.2: Alstom APS system

- *SWIMO by Kawasaki*

Kawasaki Heavy Industries in Japan has tested a next-generation LRV, called SWIMO (Smooth WIn Mover) [20].The SWIMO is an articulated three-car, 15m long tram. Powered by the Gigacell, Kawasaki's proprietary nickel metal-hydride battery, it can operate over 10 km without additional charging.

- *Hi-Tram by RTRI*

The Railway Technical Research Institute (RTRI) in Japan has also produced a hybrid LRV called Hi-Tram, which can be operated with or without an overhead or third feeder rail. The Hi-Tram can operate on both 1500 V DC and 600 V DC from the pantograph or on a 600 V DC lithium-Ion battery [21]. This system can also reduce energy consumption as well as CO2 emissions by activating regenerative braking technology and efficient energy management with onboard rechargeable batteries.

- *ACR by CAF*

CAF in Spain has been developing its rapid charge accumulator (ACR) catenary-free system (figure 9.3).

Figure 9.3: CAF ACR system

- *Sistras HES by Siemens*

Siemens has developed Sistras HES hybrid energy storage system that combines a double-layer capacitor with a Ni-MH traction battery. Moreover, Ansaldo STS in Italy is currently offering similar ground power supply technology for light rail applications.

Besides these solutions, mature technology for more energy efficient vehicles includes the use of permanent magnetic motors, design of minimal aerodynamic resistance train, reduction of weight, and thermos-efficient design of HVAC systems.

While the improvement of vehicle technology takes time and cost in general, systematic and operational approaches can provide the greatest effects on improving energy efficiency.

These systematic and operational methods include intelligent train control and optimized energy management system, in particular for LRVs with onboard battery, which are limited in

terms of power source and, without an optimized management of it, will suffer strong limitations of their performances.

9.1.1. Traction Batteries Trams

Traction batteries (or electric vehicle batteries = EVB) are used for the primary or secondary propulsion of electric vehicles. Though the majority of electric vehicles used in transport are cars and buses, advances in traction battery storage capacities and recharge times have generated new potential for their entrance into light-rail systems. Costs of traction batteries have also dropped significantly over the last decade.

Traction battery trams cycle through a number of modes of operation along its service route. Prior to use, the traction battery must be charged enough, which is done either during off service times in rail yards or while in service through catenary charging, solar panels or any other method traditionally used to transfer electricity to the tram.

Once the tram leaves the charging point and accelerates up to operational speed, the traction batteries begin to discharge and bear the power loads of the car's engines and any other auxiliary equipment such as Heating, Ventilation, and Air Conditioning (HVAC) systems or electric doors. Upon reaching operational speed, battery efficiency is maximized by only drawing power when coasting speeds reduce.

During deceleration to a stop or turning regenerative energy derived from excess heat and kinetic energy is released from the unit's traction motors back into the battery units, recharging them and further increasing battery efficiency.

9.2. Onboard battery-powered LRV rechargeable with solar panels

Similar to many other onboard battery-powered LRVs, we are going to propose a new tram with onboard rechargeable battery packs that enable running of the vehicle charging by catenary or onboard solar panels. The vehicle is equipped with newly applied lithium-polymer batteries as rechargeable energy storage device.

As summarized in Table 9.1 and according to Figure 9.4 the battery-driven tram (Cityway II) is 33 m long with seven car bodies and four motor bogies low-floor articulated.

Table 9.1: Specifications of the vehicle

Constructor	Fiat Ferroviaria (Alstom)
Structure	7 car body, 4 motor bogies
Dimension	33 m (L) × 2.4 m (W) × 3.3 m (H)
Engine power	4 × 178 kW
Max speed	70 Km/h
Weight	40 t
Power source 1	Lithium-Polymer rechargeable battery (144 kWh)
Power source 2	Solar panels (54.5 kWh)
Power source 3	Overhead wire
Acceleration	2.5 km/h/s
Braking	3.5 km/h/s or 6.0 km/h/s for emergency

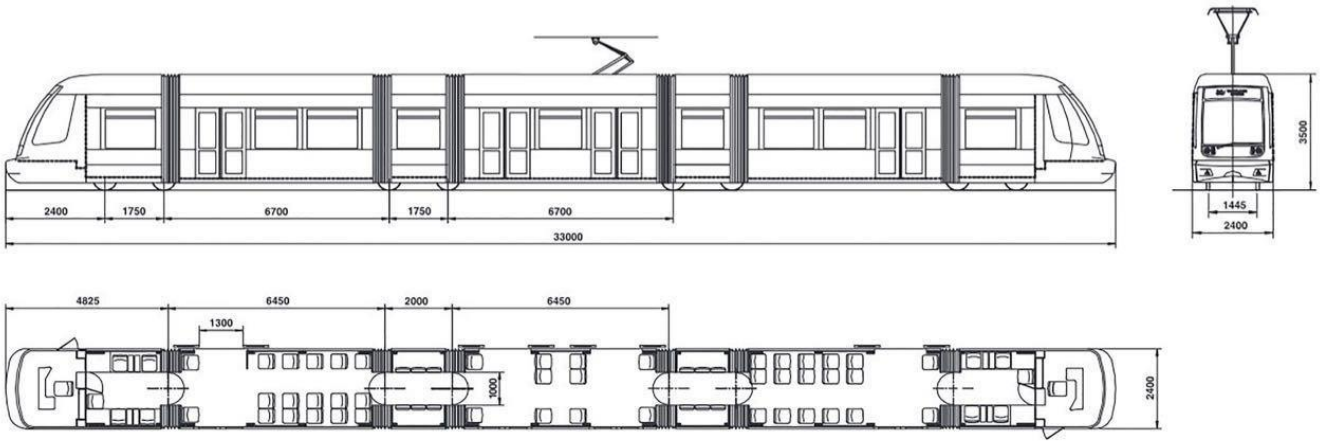

Figure 9.4: Diagram of Cityway II tram sections

The lithium-polymer rechargeable battery packs will positioned in the middle car. A major feature of the vehicle is that it can cover up to 42% (144 kWh / 340.63 kWh) of total route running without using the electrical energy after a full charge of onboard batteries, which enables environmentally friendly operation with a high level of energy efficiency and a low level of CO2 emissions consequently.

The vehicle recycles the regenerative power during braking and utilizes the energy stored in the battery as a power supply to drive the traction motors at starting or to power the auxiliary

equipment. In addition, the vehicle can receive power from the overhead line and the solar panels mounted on the rooftops.

9.2.1. Battery driving system

Figure 9.5 illustrates four steps of driving system with onboard battery-powered driving system in general.

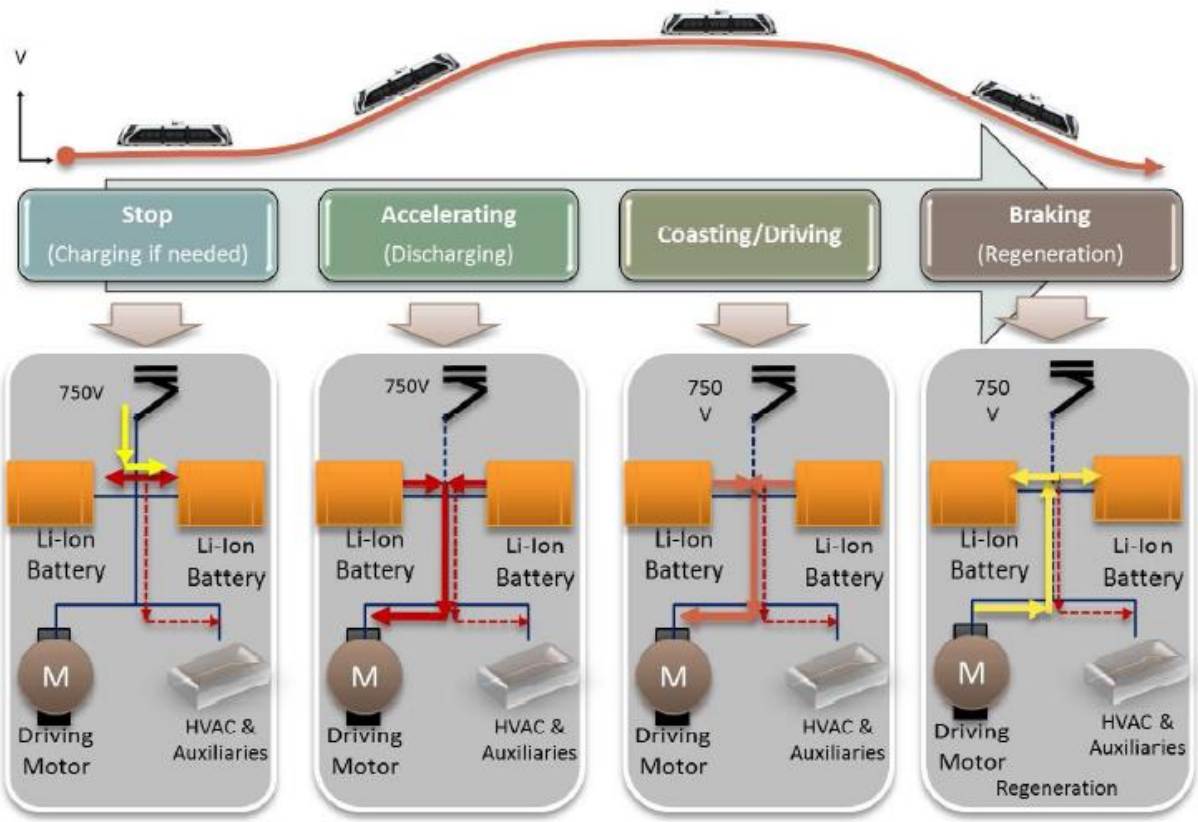

Figure 9.5: The steps of driving system

When the pantograph is in its up position and/or the solar panels are in function during sunshine, the system uses power to charge the batteries from the overhead lines or solar panels and extra power is used to operate the auxiliaries such as HVAC systems and electric doors. When the pantograph is in its down position during operation, the battery bears all power loads of the vehicle.

For acceleration or boosting, the batteries supply power to the traction motors and auxiliary equipment. In particular, the battery power is managed to minimize energy use during coasting operation.

When the vehicle brakes or decelerates during stopping, the power system charges the battery with regenerative energy released from its traction motors.

The powering system in the LRV consists of up/down converter, inverters to control the connected traction motors, static inverter to control auxiliary components including HVAC and doors and modular battery packs.

9.2.2. Lithium polymer batteries (LPB)

Compared to lithium-ion batteries introduced for recent railway vehicles, the Lithium Polymer Batteries (LPB) have less internal resistance, higher charge and discharge rate, no memory effect, longer life than those of other rechargeable batteries. In particular, the LPB has the highest energy density among the rechargeable batteries previously applied for competitive LRVs.

The LPB system in our tram contains two modular sets of pack: a series of 192 cells and a parallel of 8 cells for high energy capacity and voltage range. One battery set also consists of two column packages which are connected in series. Each battery column is composed of a parallel of 8 cells and a series of 96 cells. The system weight is less than 2,000 kg, including housing, frame, and cooling system [22].

The Battery Management System (BMS) monitors voltage, current and temperature of each cell and adjusts any voltage imbalance among them to improve the reliability of the powering system. Brief specifications of the LPB under development are summarized in Table 9.2.

Table 9.2: Specifications of lithium-polymer battery under development

Configuration	3072 Cells (8P-192S per set)
Energy density	150 Wh/kg
Weight	< 2000 kg (including housing and cooling system)
Type	Lithium-Polymer rechargeable battery
Energy capacity	150 kwh
Capacity (C)	15 Ah
Nominal voltage	614 V
Rated voltage	528 V(min. discharging voltage), ~ 806 V(max. charging voltage)
Max. power	530 kW (discharging), 587 kW(charging)

9.2.3. Driving power control

Coupled with the battery management strategies, the vehicle driving control method ensure the operation of the vehicle, by delivering high energy efficiency and maximizing driving distances.

The control method adopted is explained as follows.

1. Departure and powering: when the train is in a boosting mode for acceleration, uses battery to power the vehicle and minimizes the use of battery to supply auxiliaries.
2. Coasting: uses battery to supply the auxiliaries; when the charge of battery is below 30%, reduces the use of battery power in supplying auxiliaries;
3. Braking: uses the regenerative (electric) brake to decelerate the vehicle, the regenerated energy charges the battery and supply auxiliaries, e.g. HVAC operation;
4. In station/idle: when the train is stopped in a station, recharges the battery until it reaches a full state and maximizes the power supplement for auxiliaries.

If the train stops at a signal or in a station without charging facilities, the battery is in an idle without feeding power, we have to use the solar panels or pantograph to feed the battery.

During sunshine periods, the solar panels are in function and permanently recharge the battery by limiting the use of pantograph to recharge the battery und the control of a BMS. This driving power control cycle repeats until exhausting energy stored in battery.

9.2.4. Battery management

The BMS works in real time by switching to/from charging and discharging conditions as the vehicle accelerates and brakes. Thus, the BMS incorporate more vehicle functions than simply managing the battery. It can determine the vehicle's desired operating mode, whether it is accelerating, braking, or stopped and communicate with the train energy management system.

As a part of energy management system, main objectives of the BMS include protecting the cells or the battery from damage, prolonging the life of the battery and maintaining the battery in a state in which it can fulfill their operational requirements:

1. Cell protection: monitor and control to protect the cells from out of tolerance ambient or operating conditions, e.g. turn on the cooling fans if the battery overheats;
2. State of Charge (SOC): monitor and calculate the SOC of each individual cell in the battery to check for uniform charge in all them. The SOC can be estimated from various methods such as open circuit voltage, coulomb counting (current integration), and internal impedance.
3. Operating range setup: under normal operational requirements, maintain the SOC between 30% and 80%, which allows both high power capabilities for regenerative braking and discharge capabilities for boost. Over-discharge of battery could shorten their life and full charge would diminish charge acceptance for regenerative braking.

9.2.5. Auxiliary components power control

Among many auxiliary components in the train, the HVAC is a major target component to manage the use of energy. In spite of the limited onboard battery energy, the catenary-free tram also requires adequate air conditioning, something which greatly increases their total energy consumption. Especially in the winter months, the energy requirement for auxiliaries such as heating, ventilation and lighting may sometime exceed the amount of traction energy.

Simulation results of operational power consumption also indicate that power consumption for HVAC operation is over 30% of vehicle driving energy consumption during regular operation. Therefore, energy management system has to include the thermal isolation of car bodies and window glasses as well as in reducing unnecessary door openings.

It is experienced that, by adjusting load of HVAC upon vehicle conditions, e.g., door opening/closing, number of passengers and battery SOC, the Intelligent HVAC control in the EMS can save overall energy consumption by at least 10%.

9.2.6. Performance evaluation

Table 9.3 shows simulation results of vehicle power requirement [23] both in boosting and regenerative braking by Korea Railroad Research Institute.

Table 9.3: Simulation results of vehicle power requirement (Seoul)

Coasting speed	Roundtrip time	HVAC	Energy consumption		Regenerative energy	Net energy consumption
[km/h]	[min]		Traction effort [kwh]	Auxiliary units [kwh]	[kwh]	[kwh]
40	39.3	On	112.5	47.16	50	109.66
40	39.3	Off	112.5	16.96	50	79.46
40	39.3	control	112.5	34.51	50	97.01

Overall energy requirement during actual operation has been simulated with a LRV track profile of 11.4 km including 13 stations in Seoul, Korea. The vehicle was a 46 t fully loaded vehicle, with 750 V DC of boosting voltage, 825 V DC of regenerative voltage and 72 kVA of auxiliary power unit.

Tractive effort is discharging onboard battery, as well as the braking effort is regeneration power able to charge the onboard battery. Because of different consumption from HVAC part to seasonal reasons, in these results have been considered the maximum HVAC load.

Comparing the results of the table above with the characteristics of Cityway II tram operating on line 8 in Rome and considering the onboard battery and solar panels mounted on the rooftops, the results summarized in Table 9.4 would be expected.

Table 9.4: Expected results of vehicle power requirement (Roma)

Coasting speed	Roundtrip time	HVAC	Energy consumption		Regenerative energy	Solar energy	Net energy consumption
(km/h)	(min)		Traction effort (kwh)	Auxiliary units (kwh)	(kwh)	(kwh)	(kwh)
27.6	66	On	238.51	102.12	106.7	54.6	179.33
27.6	66	Off	238.51	35.64	106.7	54.6	112.85
27.6	66	control	238.51	80.6	106.7	54.6	157.81

Net energy consumption is 179.33 kWh when HVAC was turning on throughout the round trip of the vehicle. As a result, about 30% of total energy saved in the battery was used in operating HVAC component, which indicates that efficient energy management of the auxiliary power units can greatly reduce the net power consumption. In fact, over 10% of energy has been saved when the systematic energy management system was applied.

As shown in Table 9.3, 47.4% of overall energy required by a tram operating on line 8 could be saved through energy storage and solar energy.

Considering the additional weight from onboard battery and mounted solar panels, we make some calculation to identify the effect of the additional weight on the tram performance and demand power.

The weight that has been added to the tram tore is 2.6 tons from which 2 tons is for battery and 600 kilograms (30×20 kg) is for panels, according to the following equations and weight of tram with passengers (Table 6.1) which is 53.5 tons could be measured the energy consumption increase.

$$F = m.a$$

$$P = F.V$$

$$E = P.t$$

Since m* = 53.5 + 2.6 = 56.1 tons respect of m = 53.5 tons, 4.9% has been increased therefor F* and also P* will be increased as well. Table 9.5 shows the energy consumption corresponding the additional weight and the percentage that generative energy can supply.

Table 9.5: Expected results of power requirement of updated vehicle by additional weight

HVAC	Energy consumption		Regenerative energy	Solar energy	Net energy consumption	percentage of recovery
	Traction effort (kwh)	Auxiliary units (kwh)	(kwh)	(kwh)	(kwh)	
On	250.2	107.23	106.7	54.6	196.13	45.13
Off	250.2	37.39	106.7	54.6	126.29	56.09
control	250.2	83.69	106.7	54.6	172.59	48.08

As shown in Table 9.5, net energy consumption is affected by additional weight and about 20 kWh is increased whereas 45% of overall energy required by a tram operating on line 8 to which added the weight of battery and panels, could be saved through energy storage and solar energy.

10. Conclusion

This thesis has focused on creating a simplified calculation method for powering a tramway network by solar energy and verifying that the method produces useful and accurate results by comparing the simulation output with measurement data from another solar light rail proposals of some countries around the world. The result of this work is a demonstration of energy consumption that utilize the calculation method to fast and easy determine if a tram is correctly equipped by solar panels on the roof and onboard storage capability at the middle.

The basis in the created measurement is a theoretical model of the energy need of a tram and recovery energy of solar and released energy during the braking. The tractive and resistive efforts, tram characteristics, the solar generative energy by photovoltaic panels and the regenerative energy by onboard battery which form the basis of the theoretical model have been derived from well-established physical theorems and reliable formulas from the train industry and solar energy industry, which are proven to give reliable results.

In spite of the mature technology of railway vehicle and system, many improvements concerning energy saving are still possible. The very different types of operation call for different methods of energy optimization. While the improvement of vehicle technology takes time and cost in general, the greatest effects will arise from a systematic and operational approach of the railway system based on sophisticated train control and management systems. As described in this research, the energy storage devices with recharging capability by solar energy have reached a level of reliability that is necessary for transport application. Their benefits cover energy saving as well as improved system performance, together with possible reductions of greenhouse gas emission. Moreover, improvement of energy efficiency through systematic and operational optimization can be another aspect to further improve the efficiency of railway energy.

Local technical optimizations will result in smaller overall effects, most of which are attributable to the very mature level of technology that has been reached today.

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