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Application of the solar glass in automotive industry

Study of implementation of thin, semi-transparent CdTe solar panels in public transportation system

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Abstract — In recent years, building integrated photovoltaic (BIPV) applications have gained not only the considerable interest, but also becoming widespread over the world. Different semi-transparent photovoltaic transparency levels can be used in such applications. This thesis aims to investigate the energy performance and utilization of a CdTe thin-film based semi-transparent PV in automotive world.

Outdoor experimental setup was built in Avigliana, Italy, in order to investigate the performance of 35%, 25%, 20% and 5% CdTe thin-film based semi-transparent photovoltaic panels. The comparison was made with panels mounted with inclination of 89 deg., following the glass inclination of an electric bus, implied by Turin public transportation company. Data from the experimental setup was collected during different days and under different weather conditions.

Following that, another experiment took part in the streets of Turin, Italy, with the goal of simulating the working conditions of the public transportation services. Three CdTe specimens were mounted on the food delivery backpack, positioning them on left, right and rear sides. This setup was then used by ordinary delivery rider during his working shifts, collecting the data about "real world" behavior of the solar panels and their actual efficiency, working in case of the light and shading disturbances.

The last point of the thesis was the substitution of the public bus windows with semi-transparent solar panels, studying their efficiency, theoretical energy profit and the final cost calculation. Results of the first part of experiments proved that, CdTe panels with lower transparencies have better thermal insulation property than higher transparency ones.
The outcomes of the second part, showed that disturbances decrease the overall efficiency of the panel by up to 20%.
The last study, evaluated that the theoretical gain of the solar panels mounted to the bus can still provide a significant amount of energy.

Index Terms — photovoltaic cells, ultra-thin film for public transportation, cadmium compounds, CdTe, solar energy, solar power generation

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Chapter 1: Introduction

1.1 Background

The energy demand in the world is increasing at a rapid rate. As the countries become more and more industrialized, per capita consumption of electricity increases. While on one hand growth brings prosperity to a nation it also puts immense pressure on the earth's resources. Fossil fuels – coal, petroleum have been the main energy source for the last two centuries. However, these reserves are fast depleting. Moreover their increased usage generates vast amounts of greenhouse gases that put the nature at risk. Alternative forms of energy are an urgent need of the hour.

Turin, like many other cities, faces the pressing need to create a more sustainable urban environment. It has recognized the importance of embracing renewable energy sources and exploring innovative solutions to power its public transportation systems. Renewable energy technologies, such as solar power, offer promising opportunities to reduce reliance on fossil fuels and mitigate the environmental impact.

Solar energy can be a major source of energy for this planet's needs. It is available in abundance and is environment friendly. The photovoltaic (PV) technology now a major industry exists, which can directly convert solar energy into electricity. The advantage of the PV technology is that it is modular in nature that is a system size can range from few kWs to few MWs simply by placing modules in series and parallel. Also photovoltaic modules are passive no noise and no pollution emitting systems that can be placed anywhere from deserts to rooftops. It is estimated that 30% of land covered by solar modules are enough to take care of almost all of earth's electricity needs. In the wake of depleting fossil fuel reserves, photovoltaic cells have a very important role to play.

In particular, solar energy has gained significant attention due to its abundance, sustainability, and versatility. The integration of solar panels on public transport vehicles has emerged as a potential solution to harness solar power and reduce both operating costs and environmental footprints. In this context, ultrathin transparent CdTe solar panels have garnered interest as a highly efficient and aesthetically pleasing option for integrating solar power generation into various surfaces, including vehicle roofs and sides.

1.2 Research objectives

By adopting semi-transparent CdTe solar panels on public transport, we can tap into the vast potential of solar energy and make substantial strides towards its renewable energy goals. The integration of these panels offers numerous benefits, including reduced reliance on nonrenewable energy sources, lower operational costs through energy savings, and a reduced carbon footprint. Furthermore, the use of solar energy aligns with Turin's commitment to sustainability and positions the city as a leader in clean and green transportation initiatives.

However, the integration of semi- transparent CdTe solar panels on public transport in Turin also presents several challenges. Technical considerations, such as panel efficiency, durability, and compatibility with existing vehicle infrastructure, need to be addressed. Environmental assessments are required to understand the impact of solar panel integration on the overall carbon emissions and ecological footprint of the public transport system. Moreover, economic evaluations are necessary to determine the financial viability and return on investment of implementing solar panels. Additionally, public acceptance and stakeholder engagement are crucial for the successful adoption and integration of solar-powered public transport solutions. This thesis aims to delve into these considerations and provide a comprehensive analysis of the integration of semi-transparent CdTe solar panels on public transport in Turin. By examining the technical, environmental, economic, and social aspects, this study seeks to contribute to the growing body of knowledge on sustainable transportation solutions and provide insights for the successful implementation of solar-powered public transport initiatives in Turin and beyond.

1.3 Scope and limitations

The former includes:

1. The research will focus on the integration of semi-transparent CdTe solar panels on electric buses from BYD in Turin, specifically evaluating their performance, efficiency, and feasibility. These busses were chosen because of they are currently in use by public transportation service company.
2. Different types of semi-transparent CdTe solar panels will be assessed, considering parameters such as thickness, light absorption efficiency, and transparency, to determine their suitability for integration on public transport vehicles.
3. The impact of inclination angles, in particular 89° on solar power generation will be investigated, analyzing how panel orientation affects energy production.
4. The study will collect and analyze data on solar power generation, energy efficiency, and cost analysis to evaluate the effectiveness of CdTe solar panel integration on public transport in Turin.
5. The research will be conducted within the context of Turin's public transport system, taking into account operational patterns, environmental and geographical factors.

6. The potential benefits of solar panel integration, such as energy savings, reduced carbon emissions, and financial implications, will be assessed.

While the limitations:

1. The performance of the solar panels may be influenced by weather conditions, including variations in cloud cover and sunlight intensity, which could impact the accuracy and consistency of the data collected.
2. Due to resource and time constraints, the study will be focused on a limited number of the random routes, which may limit the generalizability of the findings to the entire public transport system in Turin.
3. Technical challenges, such as space constraints for panel installation or compatibility issues with the existing electrical system of the buses, may arise during the integration process, potentially affecting the overall performance and feasibility of the system.
4. External factors beyond the scope of the study, such as changes in government policies or advancements in solar panel technology, may influence the long-term viability and scalability of the integrated solar panel system.

By clearly outlining the scope and limitations of the research, the study can maintain scientific rigor and provide a comprehensive understanding of the research boundaries and potential constraints.

Chapter 2: Thin film solar cells

2.1 Introduction

A solar photovoltaic cell is a device that converts light energy from the sun into electrical energy. This is achieved by a semiconductor p-n junction, which on action of light results in the charge separation across the junction through the existing built-in electric field in the depletion region as shown below in figure 1.

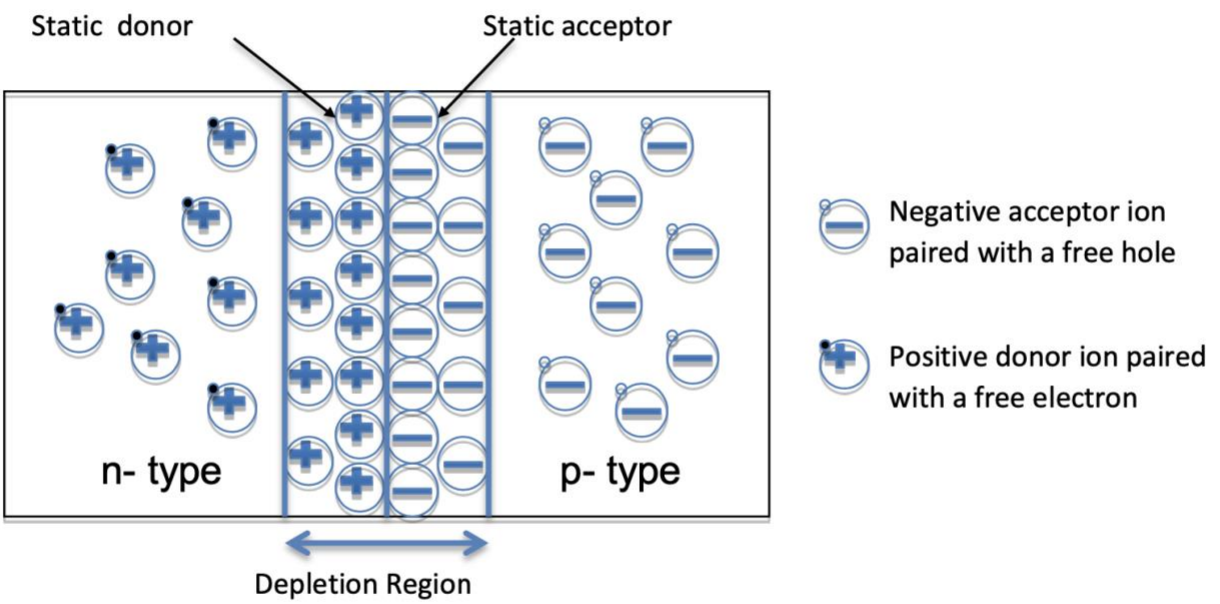

Figure 1 – The schematic representation of a simple p-n junction with a depletion region formation

A p-n junction can act as a photovoltaic device. A p-n junction is formed by amalgamation of n and p-type semiconductors. Most commonly this is achieved using only one semiconductor, for example c-Si by doping the material suitably within the bulk of the material to form p-n homo-junction. The two semiconductors differ in that n-type semiconductors carry a majority of mobile (free) electrons shown together with a positive donor atom (doped by a Vth group atom) and the p-type semiconductors carry a majority of free holes (holes are vacancies created by electrons - carry unit positive 5 charge) shown together with a negative acceptor atoms (doped by a IIIrd group atom), maintaining electrical neutrality throughout the bulk crystal.

2.2 P-N Junction principle

A classical p-n junction is shown above in figure 2. The device action starts with the formation of the junction. Since both sides of the junction have different concentrations of mobile charge carriers, diffusion starts across the junction. The on-going diffusion of charges leaves behind a region of oppositely charged fixed atoms i.e. electrons will diffuse from n-type semiconductor to the p side of the junction leaving behind positively charged fixed atom sites in the n side. Thus, as diffusion of holes and electrons proceeds, static charges build up both in the p-type and n-type materials close to the junction. This charged area is called the space charge region or the depletion region. This accumulation of oppositely charged regions gives rise to an electric field in the semiconductors close to the junction region. The electric field opposes the diffusion process. The two conflicting transfer process rates of drift (electric field induced) and diffusion give rise to a region around the junction, which is depleted of any free carriers and this region is left only with a sheath of positive donor and negatively charged acceptor atoms which will be immobilised and lead to an electric field and hence a potential across the junction. The electrostatic potential difference resulting from the junction formation is called the built-in voltage, Vbi.

2.3 Photovoltaic action

When photons carrying energy more than certain threshold energy (threshold energy being the band gap of the material on which the photon is incident) are incident on the material electrons are excited from valence band to the conduction band and electron hole pairs are created in the process. The charges get separated in the depletion region and accumulate at the terminals. This accumulation of charge at terminals gives rise to a potential difference which is called open circuit voltage (Voc). Now when the two ends of the p-n junction are connected together without load, the resultant current is called short circuit current (Isc). A more common parameter is the current per unit area or the current density (J), which will be used in later in the following chapters.
The open-circuit voltage, Voc, is the maximum voltage available from a solar cell. The maximum voltage occurs when the total net current through the solar cell is zero. The open circuit voltage can be given by

$$Voc = (nkT/ q) \ln (Jsc/ Jo + 1)$$

Where n, is the ideality factor,
K, is the Boltzmann constant
T, is the temperature
q, is the electronic charge
Jo, is the dark saturation current density, when the voltage across the solar cell is zero.
Jsc, the short-circuit current density is the current per unit area through the solar cell

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Jsc is the maximum obtainable current density from a solar cell and is achieved when the end contacts of the cell are short- circuited. In an ideal cell Jsc is equal to the photocurrent generated by the cell when exposed to light.

The fill factor (FF) is defined as the ratio of the maximum power from the solar cell to the product of Voc and Isc. The fill factor is a measure of the "squareness" of the J -V curve in forward bias. It is given by

$$FF = (V_{mpp} \times J_{mpp}) / (V_{oc} \times J_{sc})$$

Vmpp and Jmpp are the voltage and current density values of the solar cell when the net Power (Pmpp) output of the cell is maximum.

Efficiency (η) is defined as the ratio of maximum power output from the solar cell to the incident illumination density Pin. It is typically measured at standard conditions of Pin 1000W/m2, T= 298 K and AM 1.5 .it is given by

$$\eta = (V_{oc} \times J_{sc} \times FF)/P_{in}$$

Solar cells are analysed using J-V curves such as shown below. The general expression for the current produced by a solar cell is

$$J = J_{sc} - J_o(e^{qV/kT} - 1)$$

Voc and Jsc are indicated in the figure 2. The area under the J-V curve is the power density, P obtainable (theoretical) from the solar cell. The maximum power obtainable is called the maximum power point (Pmpp).

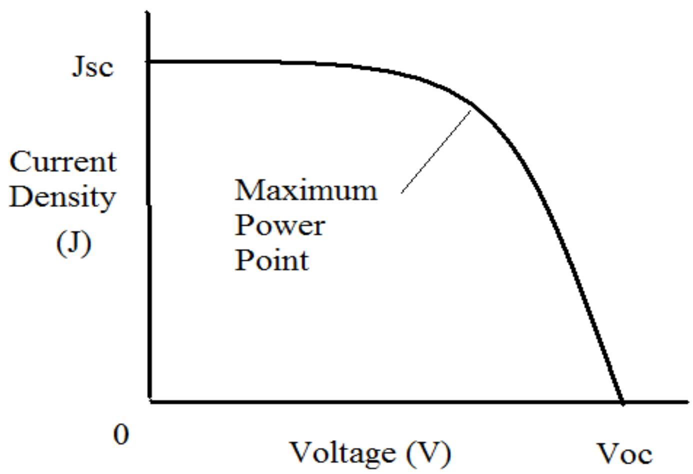

Figure 2 – J-V curve of a typical solar cell when measured across a resistive load.

An equivalent circuit is usually used to depict a practical solar cell. The figure 3 below shows the equivalent circuit of a practical solar cell. Ideally a solar cell should have an infinite shunt resistance (Rsh) and zero series resistance (Rs). Unlike an ideal solar cell, Rs and Rsh are present in a practical solar cell. These two parasitic resistances Rsh and Rs impede the performance of a solar cell. Shunt resistance is caused due to imperfections in crystal structure of the materials. Shunt resistances are usually manifested as pinholes. Series resistance is the resistance of the bulk of the materials as well as the resistance at the contacts.

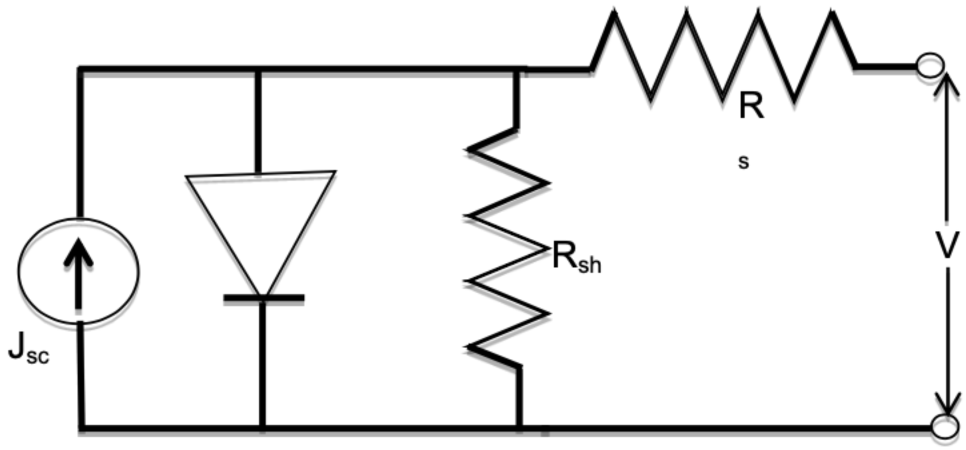

Figure 3 – Equivalent circuit representation of a non-ideal solar cell

2.4 Cadmium Telluride

CdTe is a II-VI compound with a direct band gap 1.45 eV with semiconducting properties making it one of the most potential solar cell materials. The n and p-type doping is controlled by the relative vacancies of Cd or Te atoms. The ease of process, generally vapour transport and close space sublimation to obtain both CdTe and CdS layers make it best among all PV technologies in terms of payback time.

2.4.1 Properties of CdTe

CdTe is an optimum material to be used as absorber layer in thin film solar cells because of its properties: CdTe has an energy gap of 1.45 eV, very well suited to absorb the solar light spectrum. The absorption coefficient for CdTe in the visible light range is > 105 cm^{-1}. Also the band gap between conduction and valence levels in CdTe is direct. In effect even a small thickness of cadmium telluride ~ 1 µm is sufficient to absorb majority of photons from incident light.
A variety of methods can be used to prepare CdTe. The advantage of CdTe lies in that as-deposited films made from different methods are similar in structure and electronic properties.

CdTe predominantly exists in zinc blende structure. Each Cd atom is tetrahedrally surrounded by four Te atoms and vice versa. The predominant orientations observed for CdTe thin films are the (111) and (110) orientations. The typical unit cell dimension is 6.481 Å and CdTe bond length is 2.806 Å.

2.4.2 Deposition methods for CdTe

CdTe forms stoichiometric films when heated sufficiently typically above 600 °C. The most common CdTe film deposition method is high vacuum deposition; CdTe is evaporated from a heated crucible and condensed on a substrate positioned in front of this crucible inside a vacuum vessel. The crucible and source material are kept at a temperature around 700 °C, and the substrate is heated to temperatures between 200 °C and 400 °C.

(a) Physical vapour deposition
In this form of deposition vapours of Cd and Te exist in equilibrium with CdTe solid which deposits on the substrate. Either elemental cadmium and tellurium or CdTe compound can be used as source for Cd and Te_2 vapours. Source temperature, source to substrate distance and total pressure are crucial parameters in this type of deposition. The source temperature is between 700- 900 °C, while the pressure is around 10^{-6} Torr.

(b) Close-spaced sublimation (CSS)
A modified version of PVD is CSS where substrate is maintained at temperatures close to 500 °C. The evaporation source is made in the form of a flat plate essentially the same size as the substrate and is placed in close distance (typically 2-3 mm) in front of the source. The source, CdTe powder is placed in a graphite boat. Thermocouples are used to monitor and control the temperature. Tungsten lamps may be used to heat the source and the substrate. Both the source and the substrate should be heated independently of each other. An insulator is provided between source and substrate. An inert gas such as N_2, Ar or He is used as ambient at pressures of 1mbar or higher. Source temperature, substrate temperature, source/substrate spacing and pressure are important parameters. The CSS method has yielded the highest small area efficiency.

(c) Vapour Transport Deposition
In CSS, vapour transfer occurs by diffusion. In VTD vapour transfer is by convection using a carrier gas. It involves moving substrates, which allows higher deposition rate. A vapour is saturated with Cd and Te, which delivers the gases to the substrate. The substrate is maintained at a cooler temperature where CdTe gets deposited. The carrier gas flow rate can be controlled which controls the deposition rate.

(d) Sputtering
CdTe films can also be deposited by radio-frequency magnetron sputtering from compound targets. This process is carried out in a vacuum ambient at pressures around 10 mTorr. In this process, an inert gas such as Ar is used as ambient. Under high vacuum plasma conditions are created by applying an electric field. As a result of the electric field Ar atoms are bombarded onto CdTe targets. Cd and Te atoms are then sputtered and condense on substrate. The sputtering process is typically a low temperature method with temperatures around 300 °C. The method allows good process control. Deposition rates are typically about 100 nm/min.

(e) Spray Pyrolysis /chemical spraying
Spray pyrolysis involves the atomization of the precursor solution, spray formation followed by the chemical reaction on a hot substrate. An aerosol precursor solution is prepared. The solution contains heat decomposable compounds of cadmium and tellurium. The solution is then sprayed onto a hot substrate. The substrate is usually maintained at a temperature of about 500 °C. The pH, concentration and quantity of the solution are important parameters as is substrate temperature. Other parameters that affect film property are spray rate, nozzle to substrate distance and nozzle diameter. It is a non-vacuum technique.

(f) Electrodeposition
Electrodeposition of CdTe consists of the galvanic reduction of Cd and Te from Cd^{2+} and Te^{+} ions in acidic aqueous or non-aqueous electrolytes. The typical setup contains a container filled with a solution containing cadmium and tellurium ions. Two (or three) electrodes are immersed into the solution. The cathode is the typically glass/ TCO/CdS stack. The counter electrode is an inert metal electrode such as platinum.
A reference electrode is also required which determines the deposition potential of CdTe with respect to a standard electrode (Ag/AgCl standard electrode or Standard Calomel Electrode, SCE). Potentiostatic or galvanostatic conditions can be used to deposit CdTe layers. As-deposited films can be fabricated as stoichiometric CdTe, Te- rich (by increasing Te species concentration in the bath) or Cd rich (by depositing at low potentials with limited Te species concentration).

(g) Metal Organic Chemical vapour deposition
In this technique organic compounds of cadmium and tellurium are used as source with a suitable carrier gas. A metal organic chemical vapour deposition (MOCVD) system typically consists of a gas control system and a reaction tube. Common Cd and Te precursors are dimethylcadmium and diisopropyltellurium. Substrates are maintained at temperatures around 200-400 °C. A carrier gas like nitrogen carries the vapours to reaction tube. Flow rate of nitrogen is controlled which in turn controls the reaction mixture composition near the substrate. The process does not require vacuum.

(h) Screen Printing
In this simple technique, Cd, Te and $CdCl_2$ are combined together in the form of a paste and applied to the substrate through a screen. A pattern is photographically defined on a stainless steel screen. Screen printing depends on some important parameters such as: the viscosity of the paste, the mesh number of the screen (number of meshes per inch), and the pressure and speed of the squeegee. The printed film is dried and then heated to facilitate recrystallisation of CdTe layer.

2.4.3 CdTe solar cells

The CdTe solar cells can be grown in both substrate and superstrate configurations. The CdTe/CdS layers for superstrate cells are grown on transparent conducting oxide (TCO)-coated glass substrates. The glass substrate can be alkali-free glass for high- temperature processes (500-600 °C) or a low-cost soda-lime glass for growth process
temperature below 500 °C. Although both superstrate and substrate structures have been 11 tried for CdTe solar cells, better results have been achieved for superstrate structure. For flexible solar cells, substrate configuration is most suited because it does not have to be transparent that allows different types of foils such as stainless steel, polyamide, molybdenum for the growth of the flexible cells. Both the substrate and superstrate structures are shown in Figure 4 (a) and (b) respectively.

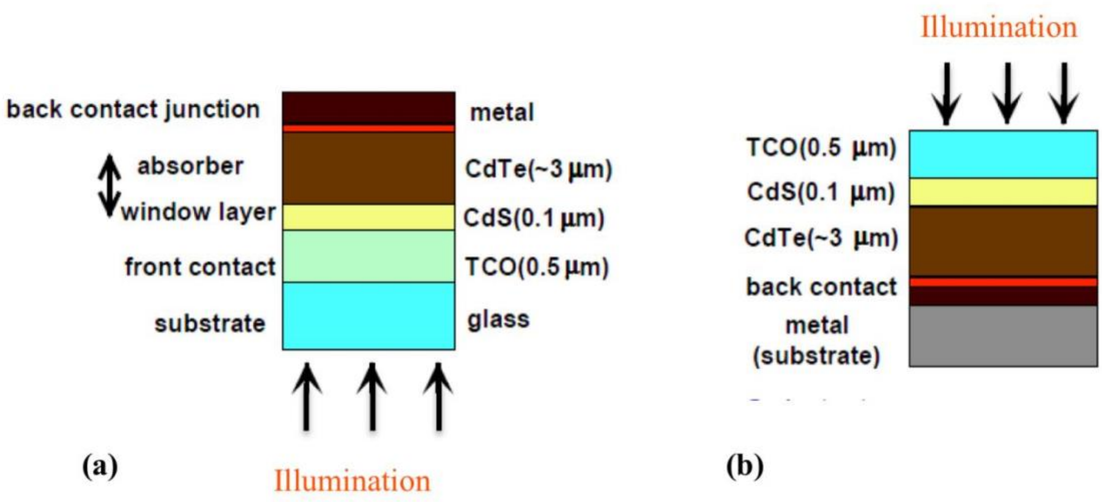

Figure 4 – Superstrate (a) and substrate (b) configuration of CdTe solar cell stack. Arrows indicate the direction of the sun rays.

The basic p-n diode junction in a CdTe based solar cell is formed between p-type CdTe absorber layer and n-type CdS window layer. The superstrate structure stack typically used for a CdTe based thin film solar cell is shown in figure above. The various layers are discussed below.

(a) Transparent Conducting Oxide

The glass layer is coated with conducting oxides such as SnO_2 (tin oxide) or indium doped tin oxide or fluorine doped tin oxide or cadmium stannate. This layer is transparent and acts as the front contact. A highly transparent and conducting TCO layer is used to form an Ohmic contact with the CdS. F-doped SnO_x [SnO_x:F (FTO)] or ITO are the most commonly used TCOs for CdTe solar cell. Intrinsic SnO_x layer between CdS layer and TCO layer are used that prevents shunts through pinholes in CdS.

(b) CdS – Window layer

As mentioned earlier, cadmium sulphide is the preferred heterojunction partner with CdTe. Cadmium Sulphide (CdS) exists in two crystalline forms namely zinc blende and wurtzite structure with alternating Cd and S atoms. Each Cd atom is surrounded by four S atoms in a hexagonal close packed structure. The S vacancies act as donors and make the CdS n-type. CdS has a wider band gap of 2.42 eV and allows most of the incident light photons to pass through and enter the CdTe absorber layer more readily. To minimise absorption in the window (CdS) layer it is very thin – in the range of 200 to 500 nm or even thinner. Like CdTe, CdS forms stoichiometric films easily and by similar methods as used for CdTe deposition. CdS layer is deposited on top of the TCO layer. Because the CdTe and CdS are mixed easily during the cell fabrication process, it leads to the formation of interfacial layer of CdS1-xTex and in effect a high quality and efficient CdTe/CdS junction is formed. Sometimes a high resistance layer is included between TCO and CdS. CdS can be deposited by a variety of processes such as sputtering, chemical bath deposition, CSS, electrodeposition, spraying, and screen printing. The processes and process conditions used are similar to those for CdTe deposition. This allows for increased compatibility between CdS and CdTe layers during manufacturing.

(c) CdTe - Absorber layer

The CdTe is deposited directly on top of CdS to form the p-n junction by any of the methods described in the previous chapter. All methods result in polycrystalline nature in as-deposited films. Typical CdTe layer thicknesses range from 3-5µm. It has been observed that post deposition heat treatment particularly in the presence of Cl- species improves CdS/CdTe junction interface, surface morphology of bulk CdTe and electrical properties of the solar cell. $CdCl_2$ is used for this treatment. The $CdCl_2$ treatment can be solution based (where the CdTe layer is dipped in cadmium chloride – methanol solution) or vapour based (where CdTe is exposed to $CdCl_2$ vapour in a closed chamber). The CdTe substrate after treating it with $CdCl_2$ is heated to temperatures between 350 - 420 °C for 15-30 min.

(d) Back contact
Under the superstrate structure, p type CdTe needs to be contacted to a metal conductor to form an Ohmic back contact. A p type semiconductor requires a metal with high work function to form an Ohmic contact. CdTe forms a Schottky barrier with most metal back contacts. To overcome this problem researchers use buffer layers to make the surface of CdTe a p+ rich surface. A variety of buffer layers are used for this purpose. A few chemical techniques such as the bromine- methanol etch or nitric- phosphoric acid etch may also be used. Dry treatment processes include exposure to ion beam under vacuum conditions.

2.5 Thin transparent CdTe solar panels

Thin semi-transparent CdTe (Cadmium Telluride) solar panels are a specific type of photovoltaic technology that has gained attention for its unique properties and potential applications. Unlike traditional silicon-based solar panels, CdTe panels are constructed using thin-film technology, which allows for a lightweight and flexible design.
Key features of thin semi-transparent CdTe solar panels include:

1. **Thin and Lightweight Design:** CdTe panels are significantly thinner and lighter compared to traditional silicon-based panels. This thin-film technology enables their integration into various surfaces, such as glass, plastics, or even curved structures, without compromising their performance.
2. **High Light Absorption Efficiency:** CdTe semiconductors have a high absorption coefficient, allowing them to efficiently convert sunlight into electricity even under low-light conditions. This attribute makes CdTe panels suitable for diverse environments and locations with varying levels of solar irradiation.
3. **Transparency:** One of the unique characteristics of thin transparent CdTe solar panels is their transparency. They are designed to allow a certain level of light transmission, enabling their integration into windows, skylights, or other transparent surfaces. This transparency feature offers aesthetic advantages and opens up new possibilities for incorporating solar power generation into architectural designs.
4. **Flexibility and Durability:** The thin-film nature of CdTe panels gives them inherent flexibility, allowing them to conform to curved or irregular surfaces. This flexibility facilitates their integration into a wide range of applications. Furthermore, CdTe panels have demonstrated good durability and resilience against environmental factors, ensuring long-term performance and reliability.

The utilization of thin transparent CdTe solar panels in public transport systems, such as on buses or tramway roofs, presents several benefits. Their lightweight and flexible nature make them suitable for integration into existing infrastructure without adding excessive weight or altering the

vehicle's aerodynamics. The transparency feature of CdTe panels can also contribute to the overall aesthetics of the public transport vehicles, seamlessly blending with the design.
Furthermore, the high light absorption efficiency of CdTe panels ensures effective solar power generation, even in urban environments where shading or indirect sunlight may occur. The use of CdTe panels can enhance the sustainability of public transport by reducing reliance on conventional energy sources and reducing greenhouse gas emissions.
In the context of Turin's public transport, the integration of semi-transparent CdTe solar panels offers a promising opportunity to harness solar energy and contribute to a more sustainable and energy-efficient transport system.

Chapter 3: Solar panels on public transport

The integration of solar power into public transportation systems has been an ongoing area of research and development. This chapter aims to provide an overview of existing solutions for both vehicles and infrastructure, examine the public transportation service in Turin as a case study, and highlight the specific bus model chosen for the thesis.
The research conducted in this chapter lays the groundwork for the subsequent exploration of solar panel integration and its implications for the sustainability of public transportation systems.

3.1 Introduction

During the course of my bachelor's thesis, I was working on a project, focused on the installation of solar cells on an urban electric car, specifically the Smart ForTwo, with the objective of enhancing driver comfort and extending its range.
The selection of the Smart ForTwo as the test vehicle was based on careful consideration of its total surface area, as the car's shape and overall area presented an optimal configuration for solar panel integration. In the initial phase of the project, solar cells were strategically placed on the vehicle's roof and bonnet, resulting in a modest improvement in the available battery charge.
Building upon the previous work, my current research endeavors to expand the scope of solar panel integration beyond the flat and predominantly horizontal surfaces, as demonstrated in the previous examples. This includes replacing all the windows of the vehicle with semi-transparent panels. However, the decision regarding the appropriate vehicle for this expanded approach was not a straightforward one. It involved a progressive evaluation of various vehicle types, starting with the concept of a large, luxurious SUV, followed by a full-size sedan, a small van, and ultimately arriving at the selection of a bus.

The outcome of this research, particularly the efficiency assessment of the semi-transparent glass panels, will significantly influence the potential expansion of this approach to diverse vehicle types. In this context, the key determinant for selecting the suitable vehicle will be based on the presence and extent of side-windows and panoramic roofs, as they directly impact the viability and integration potential of solar panels.

By widening the scope of solar panel integration to include non-traditional surfaces, such as windows, and considering different vehicle types, this research aims to contribute valuable insights into the efficiency and feasibility of such integrations. The findings will inform future endeavors in optimizing solar panel placement, enhancing energy harvesting capabilities, and exploring innovative strategies to harness solar energy for sustainable transportation solutions.

The goal is to calculate possible gain and evaluate the effectiveness of this solution.

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3.2 Existing solar bus solutions

Solar power integration in public transport has witnessed significant advancements in recent years. Various approaches have been explored, including the installation of solar panels on vehicle rooftops, integration of solar cells into windows, and the utilization of solar charging stations at transportation hubs. These solutions aim to harness solar energy to reduce the carbon footprint of public transport and enhance its sustainability.

Here are a few examples of existing implementations of solar panels on buses:

1. **Kayoola Solar Bus (Uganda):** it is a solar-powered bus developed by Kiira Motors Corporation, a Ugandan automotive manufacturing company. The Kayoola Solar Bus is a 9-meter city bus, relying on lithium-ion batteries to power an electric motor that is coupled to a 2-speed pneumatic shift transmission. Additional charging of the battery pack on the fly is achieved by the on-board solar system installed on the bus. Using the 70 kWh battery modules, the bus is expected to run 80 km between recharges.

Figure 5 – Kayoola Solar Bus

2. **SolaBus (Lyon, France):** Lyon, France, has implemented the SolaBus project, which involves integrating solar panels on the roof of a bus. The solar panels generate electricity to power various onboard systems, such as air conditioning, lighting, and auxiliary power, reducing the reliance on the vehicle's main battery and increasing energy efficiency.

3. **Trailar Solar Solutions (UK):** a British engineering company, that offers a vast choice of solar panel integration for commercial and private transportations. The idea is to reduce the alternator's requirement to create energy via the burning of fuel, to power all on-board

electrical equipment. The solar panel is fitted to the vehicles roof, and directly interfaced with the on-board electrical systems. Their solution consists of flexible solar panel, smart charge controller and 4G telematics system, that allows to track the solar fuel and CO_2 savings.

4. **Sono Solar Bus Kit (Germany):** developed by Sono Motors in Germany, is presented as "a versatile and straightforward solution, optimized for the most common 12-meter public transport bus types on the European market. Through a retrofit intervention, with installation of solar panels on the roof of a conventional bus, the system aims to reduce fuel consumption and inner-city greenhouse gas emissions. These panels harvest solar energy to charge the vehicle's battery, extending its range and reducing the reliance on external charging infrastructure. The Solar Bus Kit It allows subsystems like the HVAC to be partially powered by renewable energy.

Figure 6 – Sono Solar Bus Kit

These examples highlight the real-world implementations of solar panels on buses, showcasing the feasibility and potential benefits of solar-powered public transport. Each implementation varies in terms of technology, scale, and operational considerations, demonstrating the versatility of solar panel integration in the public transportation sector. However, the existing solution is limited to covering the rooftop of the vehicle, which obviously can help to lower the energy consumptions, but works only as auxiliary power source. While in my case the energy gain might be enough to also increase notably the range of the vehicle, consequently decreasing its time requested to recharge.

3.3 Existing examples of implementation

Numerous cities and regions have successfully integrated solar-powered solutions into their public transport systems, offering valuable case studies. Unlike previous approaches, where photovoltaic panels were directly mounted on buses to directly charge the batteries, these cities now harness solar energy to power the public transport grid and other facilities. This approach shows higher efficiency and better energy distribution.

- **San Francisco, USA:** The San Francisco Municipal Transportation Agency (SFMTA) implemented solar-powered bus shelters equipped with solar panels. These panels generate electricity to power lighting, digital signage, and other amenities at the bus stops, reducing energy costs and promoting sustainability.

- **Lusail, Qatar:** Lusail Bus Depot, which is considered the world's largest electric bus depot, in line with the Ministry of Transport's effort to provide an integrated and sustainable public transit network in Qatar, the new electric bus depot includes some 11,000 PV solar panels to generate power daily to feed its buildings.

- **Melbourne, Australia:** Solar energy to power the tram network. The Numurah Solar Farm, just opened, prides itself to be the largest facility in Victoria state (Australia). The 128 MW farm covers 515 hectares with some 374,000 solar panels. It is owned and developed by Neoen, a French renewable energy producer, and was built at a cost of some 200 million dollars. Its energy production of 255 GWh yearly, put together with the Bannerton Solar Farm owned by Foresight Solar Fund, is enough to power entirely Melbourne tram network, composed by 450 trams on 28 lines.

These case studies demonstrate the successful integration of solar energy in public transport systems, highlighting the benefits of reduced operating costs, increased energy independence, and environmental sustainability. It can be clearly seen; these solutions are gaining momentum as viable and sustainable options for enhancing urban mobility while reducing carbon emissions.

Figure 7 – Lusail Bus Depot

By examining these current trends and case studies, it becomes evident that solar-powered public transport solutions are concentrated in covering the transportation hub with solar panel, which will then provide energy to the vehicles. Which is for sure the best implementation in case of stationary buildings, combining with solar powered vehicles could help us to completely move to solar energy.

3.4 Potential integration sites

The choice to integrate semi-transparent panels on the side windows stems from the recognition that solar energy harvesting can be extended to previously underutilized areas of the vehicle. By replacing the conventional windows with semi-transparent panels capable of capturing solar radiation, the total surface area available for energy generation is expanded, leading to a potentially higher energy yield.

Beyond the energy benefits, the integration of semi-transparent panels on the side windows of the bus holds the potential to enhance passengers' comfort. These panels can be designed to maintain a suitable level of visible light transmission, ensuring sufficient interior illumination while preserving privacy and minimizing glare. Moreover, the semi-transparent nature of these panels can offer a reduction in the transmission of heat and UV radiation into the passenger compartment, leading to improved thermal comfort for the occupants.

The selection of a bus as the preferred vehicle for this integration is driven by its inherent characteristics. Buses typically possess a larger surface area, including an extensive expanse of side windows, making them an ideal platform for integrating solar panels. By capitalizing on the vast window surface, the solar panel integration can maximize energy capture potential, contributing to increased overall energy efficiency and reducing the reliance on external charging infrastructure.

The transparency level of side windows on a bus can vary depending on several factors, including legal requirements, safety regulations, and specific design choices. However, it is common for side windows on buses to have a moderate level of transparency that allows for visibility both from the inside and outside of the vehicle.
In many jurisdictions, there are regulations governing the minimum level of visible light transmission (VLT) that side windows must comply with. VLT refers to the percentage of visible light that can pass through the window. The specific VLT requirements can vary between regions and may be different for the front, rear, and side windows of the bus. For example, a typical requirement might specify a minimum VLT of around 70% for the front side windows and a lower minimum VLT of around 20-50% for the rear side windows.
The transparency level of side windows on a bus is a balance between maintaining sufficient visibility for passengers and drivers, while also ensuring privacy, safety, and compliance with applicable regulations.
It's worth noting that regulations differentiate between the VLT requirements for standard passenger windows and windows designated for the driver's visibility and safety. That leads us to an over-complicated solution for the windshield case, so I will not consider it in the further calculations.

3.5 Public transportation service in Turin and BYD K9UB electric bus

Since I live and study in Turin, Italy, I would like to concentrate on a local infrastructure. GTT is a vital component of the city's urban mobility system. Turin has a well-developed public transport network that serves both residents and visitors, offering convenient and sustainable transportation options.
In recent years, Turin has been actively embracing electric buses as part of its efforts to reduce air pollution and promote sustainable transportation. One notable example is the introduction of electric buses manufactured by BYD, a leading electric vehicle company. BYD electric buses have gained popularity worldwide for their advanced technology, efficiency, and environmental benefits.
BYD electric buses are characterized by their use of electric propulsion systems powered by rechargeable batteries. These buses produce zero tailpipe emissions, resulting in a significant reduction in air pollution and greenhouse gas emissions compared to traditional diesel buses. The integration of electric buses aligns with Turin's commitment to environmental sustainability and contributes to the city's efforts in achieving its climate and air quality goals.

In Turin, the electric busses are represented by the K9UB model, which is a variant of the BYD K9 electric bus, specifically designed for urban transportation purposes.

BYD electric buses also offer several advantages over conventional buses. Firstly, they provide a quieter and smoother ride experience for passengers, enhancing overall comfort and reducing noise pollution in urban areas. Additionally, electric buses have lower operating costs compared to diesel buses, as they require less maintenance, have fewer mechanical components, and are less dependent on volatile fossil fuel prices.

Figure 8 – Inauguration of the BYD K9UB busses in Turin, May 2021

In terms of performance, theoretically BYD electric buses have demonstrated their capability to operate efficiently and reliably in urban environments. These buses have a sufficient range on a single charge to meet the demands of typical bus routes in Turin. The batteries can be recharged overnight or during short breaks in service, ensuring continuous operation throughout the day. Furthermore, the introduction of electric buses in Turin aligns with the broader global trend toward electrification of public transport.

Many cities worldwide are transitioning their bus fleets to electric vehicles as part of their commitment to combat climate change, improve air quality, and achieve sustainable development goals.

3.6 Significance of the research

By examining existing solutions, analyzing the public transportation service in Turin, and selecting the BYD K9UB as the bus model of interest, this chapter sets the stage for the subsequent research conducted in the thesis. The integration of solar power in public transport holds immense significance in achieving sustainable and eco-friendly transportation systems. Understanding the existing landscape and identifying suitable bus models form the foundation for further investigation into the integration of solar panels and the evaluation of their performance in improving the energy efficiency and environmental impact of public transport.

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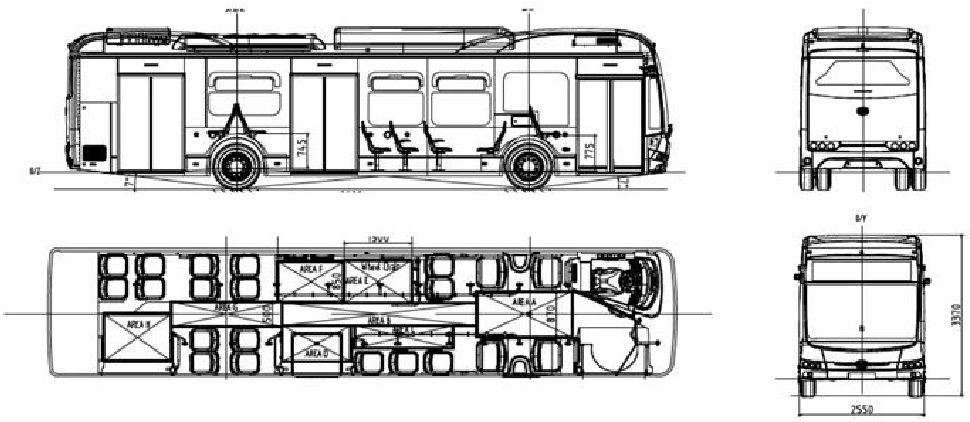
GTT GRUPPO TORINESE TRASPORTI

AUTOBUS URBANO A 2 ASSI
BYD K9UB

Serie: 9000÷9099
Scheda: UL10



Anno immatricolazione: 2021

CARATTERISTICHE PRINCIPALI

- autotelaio	BYD K9UB	
- lunghezza max	12.200	mm
- velocità max	80	km/h
- passo	5.900	mm
- carreggiata anteriore	2.200	mm
- carreggiata posteriore	2.000	mm
- raggio minimo di curvatura	8.684	mm
- tara (compreso conducente)	13.800	kg
- massa complessiva	18.968	kg
- alimentazione	elettrica	
- capacità batterie	348	kWh
- consumo SORT1	91,00	kWh/100km

CARROZZERIA

- tipo di carrozzeria (1)	BYD K9UB	
- colore	giallo-blu	
- lunghezza	12.200	mm
- larghezza	2.550	mm
- altezza	3.370	mm
- sbalzo anteriore	2.850	mm
- sbalzo posteriore	3.450	mm
- altezza pavimento min.	325	mm
- altezza pavimento max	340	mm
- porte rototraslanti	anteriore	
- porte sliding	centrale / posteriore	

CARATTERISTICHE MECCANICHE

- motore	BYD-2912-TZA		
- posizione	2 sui mozzi ruota posterior		
- cilindrata	-		cm³
- potenza max	2 x 125		kW
- coppia max	2 x 550		Nm
- rapporto al ponte	-		
- idroguida	elettroidraulica		
- freno di servizio (2)	1° asse	pneumatico	
	2° asse	pneumatico	
	-		
- freno di soccorso	1° asse	pneumatico	
	2° asse	pneumatico	
	-		
- freno di stazionamento (ruote motrici 2° ass		meccanico	
- pneumatici	1° asse	275/70 R 22,5	
	2° asse	275/70 R 22,5	
	-	-	
- cerchi in lega			

CAPACITA' POSTI PER PASSEGGERI

- posti a sedere (3)	21	21
- posti in piedi	55	54
- posto carrozzella	-	1
- posti di servizio	1	1
- posti totali	77	77

NOTE:
(1) veicoli dotati di specchietti retorvisori telecamera, sistema visione periferica, sistema allerta ostacoli
(2) veicoli dotati di dispositivo ABS-ASR
(3) veicoli dotati di rampa per accesso disabili ad azionamento manuale

Figure 9 – BYD K9UB technical characteristics

Chapter 4: Integration challenges + Feasibility Analysis

4.1 Solar panel dimensions

In this chapter, the focus is on the BYD K9UB electric bus as the target vehicle for integrating semi-transparent panels. By utilizing technical drawings and specifications provided by the manufacturer, an analysis was conducted to determine the areas suitable for the application of semi-transparent panels. This analysis takes into account the specific characteristics of the bus, including its sides and the presence of entrance doors on one side. The interesting thing about the windows, is that from the outside, we have the complete coverage with large glass panels, while technical opening for the windows is much smaller. It can we visible on the figure below.
The sides are not the only applicable parts, but also the rear window of the bus could be replaced with the solar glass.

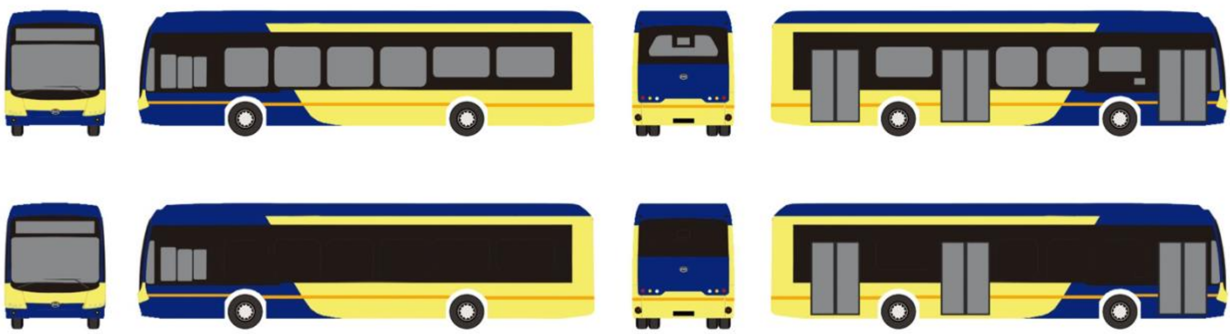


Figure 10 – Applicable panels' geometry

(The real opening is represented in gray, while the glass coverage is shown in black)

Theoretically also the doors can be replaced with solar panels, but they are subjected to a high risk of damage, due to human interaction, so I prefer to avoid modifying them. Another point to consider are the safety exists, since the solar panels are laminated and become unbreakable, leaving the doors with OEM glass can help to resolve this issue. This topic will be covered in better way in the Chapter 8.

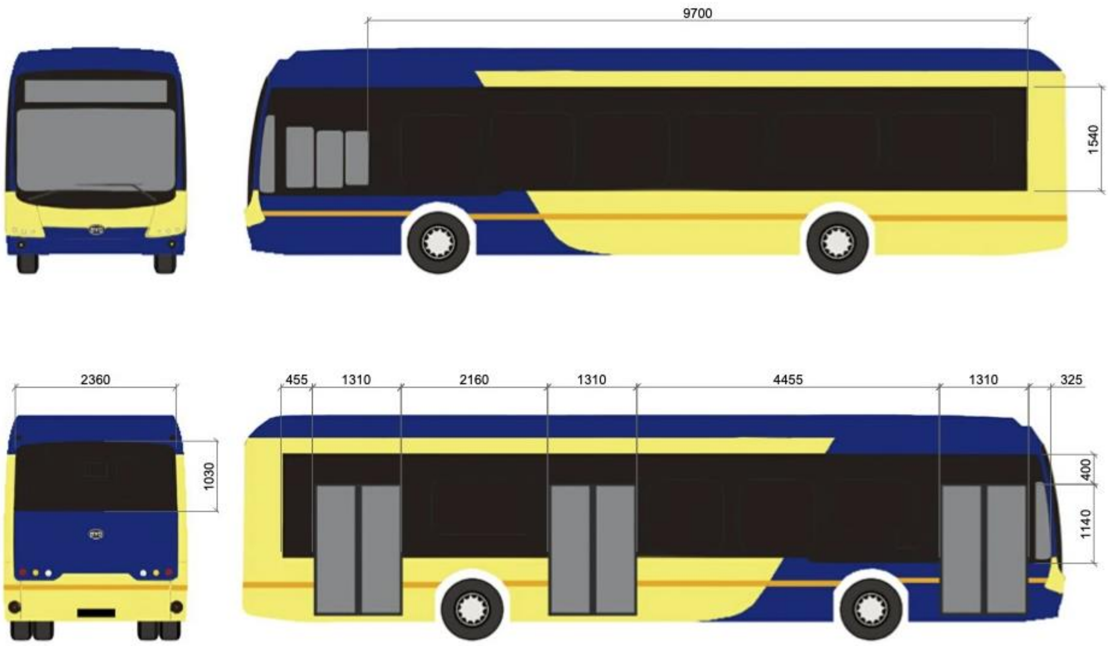


Figure 11 – Windows dimensions

Left side:
The biggest available surface of the vehicle, with the applicable window surface of 9.7 meter in length and 1.54m in height, makes a total area of 14.94 m^2. On this side the coverage would be for the whole length of the vehicle, leaving only the driver's windows untouched.

Right side:
This side will be made out of different pieces of the solar glass, with the small coverages around the entrance doors and 2 main panels between them, accumulating to the total area of 12.46 m^2. This side has more complicated geometry and slightly lower usable amount of glass, nevertheless can still provide notable amount of energy.

Rear side:
The rear of the vehicle is the smallest area, can accommodate the 2.43 m^2 glass panel.

The total coverable area of the vehicle accumulates to almost 30 square meters, to be precise **29.83 m^2** of usable surface**.**

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4.2 Rooftop solar panels

This chapter delves into the various approaches available for integrating solar panels on buses, with a particular focus on the rooftop as a standard solution. Four distinct approaches are explored, each offering unique advantages and considerations:

1. **High efficiency solar panels**
   One approach is to install simple geometry solar panels, with higher efficiency than following solutions, that are available on the aftermarket.

2. **Basic flexible solar panels on structural parts**
   This approach is to install basic flexible solar panels, these are designed for flexibility and easy integration on complicated geometry of the rooftop.

3. **Transparent panels for panoramic sunroofs**
   Another approach involves the use of transparent panels with lower transparency indexes to create panoramic sunroofs on the bus. Although the transparency index is reduced compared to standard windows, the panels still allow a significant amount of light to pass through, providing a balance between aesthetics, functionality, and energy generation.

4. **Hybrid solution**
   A hybrid approach combines the use of basic flexible solar panels on the structural parts of the bus with the installation of transparent panels for panoramic sunroofs.

It worth to notice, that BYD was experimenting with solar panels, fixed on the vehicle to supplement the onboard batteries. They were included on demo units, but not on units sold commercially. The buses with experimental set-up were other modifications of K9 model with different rooftop geometry, so it’s not suitable for K9UB application.

While the rooftop integration of solar panels is not the primary focus of this thesis, but it is essential to estimate the approximate power gain for the evaluation of overall system performance. The limitation in this case is the presence of the vehicle battery pack and HVAC modules, that divides the surface of the roof into separate groups. Additional to these, the profile of the blocks creates curvy surface, limiting the possibility to use the large solar units.
However, according to GTT, there different variations of K9UB models in use, one with complicated roof geometry, described above and the second one, with completely straight surface, allowing application of more efficient solar panels. For sake of simplicity, I considered the second variation of this bus model, with easy to estimate geometry. To provide a baseline estimation, the coverage with solar panels, similar to those available in the market, will be assumed. In this case, no need to use CdTe semi-transparent solar panels, but normal ones with

higher efficiency will be applied. Detailed calculations and simulations will be conducted to determine the expected power gain based on the surface area covered and the efficiency of the selected solar panels.

Figure 12 – Example of rooftop coverage by manufacturer from early 2011.

4.3 Technical feasibility: structural requirements

The last, but not the least thing to consider are structural and electrical integrations. In this work I will only cover evaluate theoretical part of the question, supported by virtual simulations. Starting with structural Integration, I can highlight the following points:

1. **Structural Requirements:**
   Considering the structural aspect, the size and overall dimensions will be completely following the OEM dimensions of the glass covers, while we could notice a significant weight increase, due to the density of the CdTe solar panel is double with respect to a tempered glass.
   I used the SolidWorks for the generation of a detailed body geometric model of the bus (figure below). The chassis of the bus is welded by high resistance steel and the skeletons of the vehicle body are made of aluminum alloy. To simplify the FEA process, I simplify the three- dimension model by neglecting the non-bearing components. In addition,

simplifying the cross-section shape of the components and omit the fabrication holes of the vehicle body, which can be a benefit to the mesh generation in FEA.
To understand the impact on the structure I ran a FEM analysis, leading that no structural modifications are required to host the solar panels.

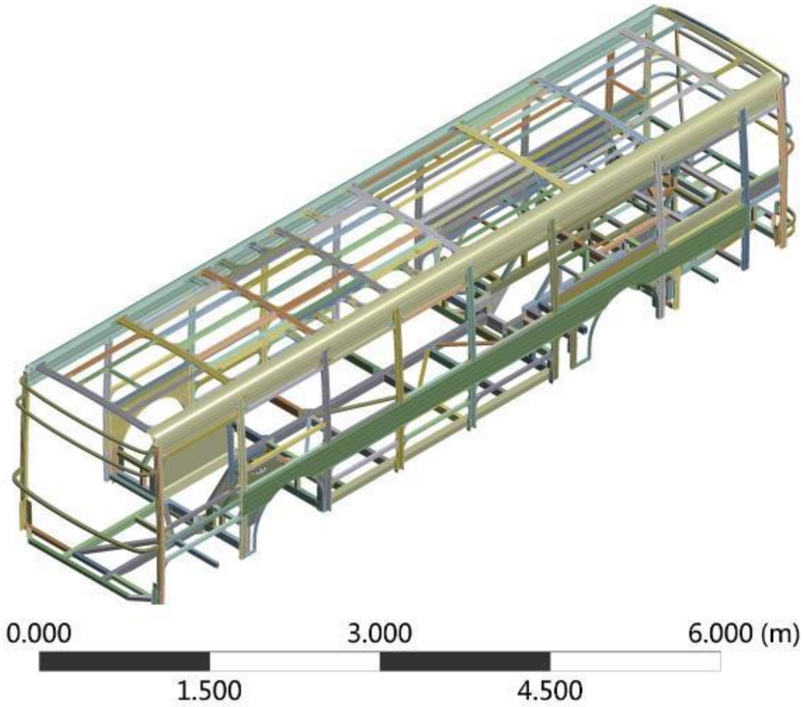

Figure 13 – CAD model of the bus in SolidEdge

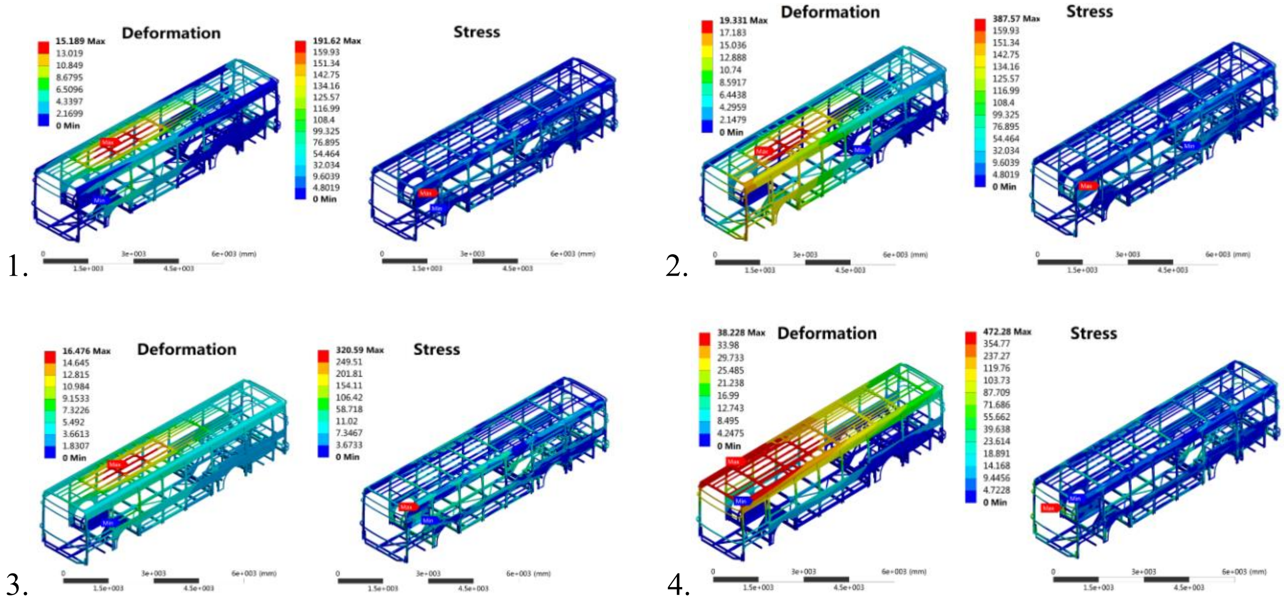

Figure 14 – Deformation and stress in 4 different cases

(From left to right: the full load bending (1), tortional (2), emergency brake (3) and steering (4) conditions)

2. **Mounting Options:**
   Body-integrated design - I would like to follow the original method, so the solar panels will substitute the OEM windows, the connection to bodywork via structural adhesive. This approach would guarantee no difference in the mechanical properties, since the solar panel characteristics are very similar to a normal automotive window. Another advantage of using this approach is having a minimal change in the aesthetics of the vehicle.
   The only consideration is the thickness, the solar panel are 1mm thicker than the original windows, so I would need to use different seals for window frames.

3. **Material Selection:**
   The physical properties of the solar panel are not the same with tempered glass, however the structural strength is compensated not only by overall increase of the thickness, but the sandwich layers of the panel provide improved bending and breaking characteristics. Having almost the same density, the substitute semi-transparent solar panels are 1 mm thicker than tempered glass, making it nearly 2 kg heavier per square meter than OEM coverage. With substitute glass area being around 30 m^2, the total weight increase will be approximately 60 kg.
   Additional positive outcome for passengers is better noise damping.

Comparison between tempered glass and solar panel		
	Tempered	**Semi-transparent solar panel**
Alteration	Not possible	Possible
Risk of Injury	Low	Low
Impact Resistance	High	Medium
Optical Distortion	High	Low
Environment Control	No	Yes
Acoustic Insulation	No	Yes
Heat Insulation	Yes,with reflective coating	Yes

Figure 15 – Comparison between OEM tempered glass and solar panel

4. **Aerodynamics:**
From the aerodynamic point of view, the potential changes in drag and wind resistance are present due to the increased thickness of the solar panels with respect to OEM tempered glass. Their influence on the vehicle's overall performance and energy efficiency is shown by the increase of the C_x by 0.01. This value can be considered irrelevant for public transportation, since the traveling speeds of the public transport merely exceed 60km/h, making the drag increase negligible.

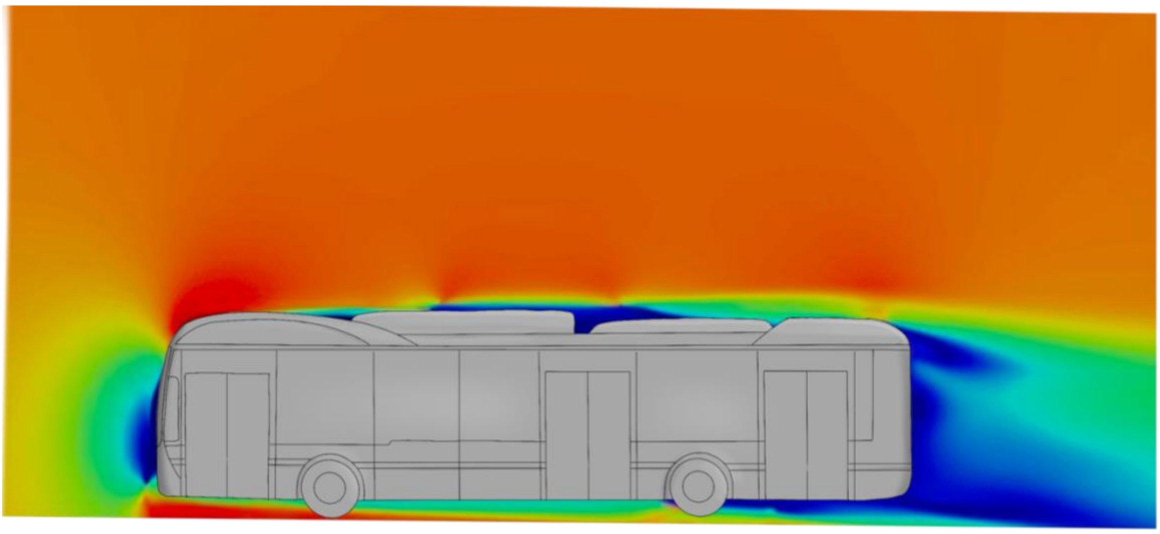

Figure 16 – CFD analysis

4.4 Technical feasibility: electrical requirements

Electrical Integration:

1. **Electrical System Compatibility:**
   The solar panels are directly compatible with existing electrical infrastructure, since studied vehicle is an electrical bus and the OEM system allows external power supply. There still be some minor modifications considering voltage requirements, current capacity, and power distribution systems. For the first and second ones the implementations of charge regulator can help resolve the issue, while the last one doesn't require any modifications.

2. **Energy Generation and Storage:**
   While for energy generation, the solar panels are required, the storage does not need of additional equipment. The OEM battery can fulfill all the requirements of the system. Additionally, the generated energy is sent only to main batteries, making the EOM system decide whether it needs to be used to charge the auxiliary batteries or not.

3. **Power Management and Conversion:**
   There is no need of power conversion, since the solar panels generate the DC current, and the electrical vehicles require the DC one too. By implementing the DC-DC boost converter which interfaces the low voltage from the solar charge controller to the high voltage bus to charge the battery pack. For safety reasons, I would like to add charge regulator before the other electrical components to optimize the power flow from the solar panels to the bus's electrical system.
   While for the rest of the system, I can rely on the original vehicle equipment.

4. **Safety Considerations:**
   What considered safety, I imply the basic protections systems for the panel – inverter parts, the fuse-based overcurrent protection will be sufficient. The working principle is implementation of branch circuit fuses and circuit breakers, each one connected to a proper solar module, so that in case of fault in one branch, the other ones will continue to supply energy.
   Since the automotive electronics is very sensible for overvoltage, 2 protection devices will be positioned. The former on in parallel to fuses, while the latter on the solar panels main array switch.

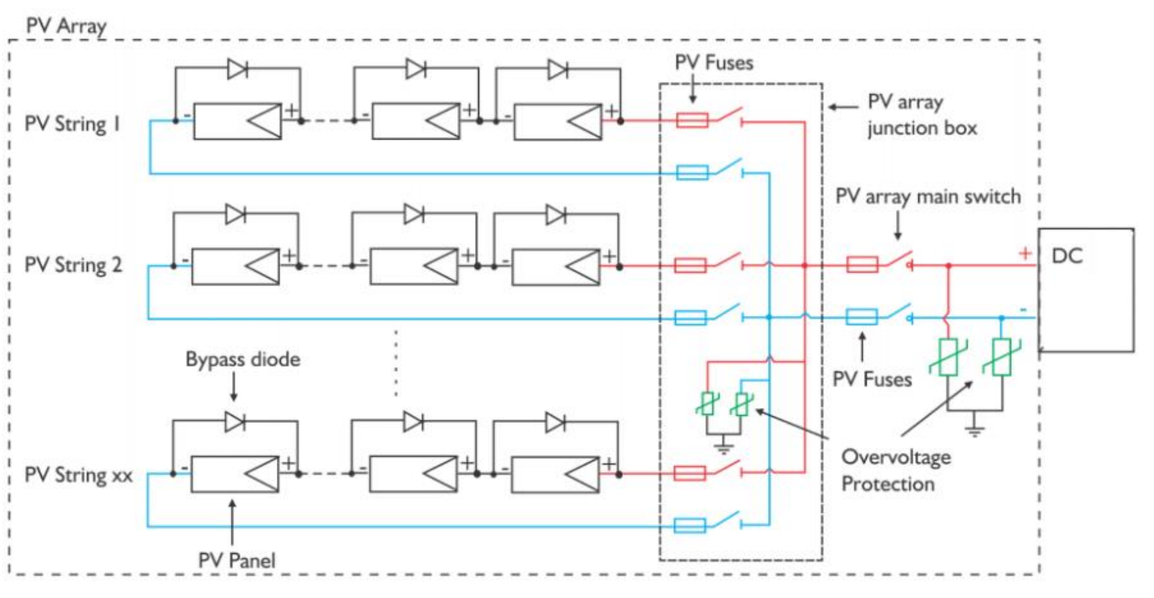

Figure 17 – Fuse-based overcurrent protection system

For the rest of the system (from inverter on) I can again rely on OEM electrical system.

5. **Monitoring and Control Systems:**
I will need to implement the monitoring and control systems to track the performance of the solar panels and optimize energy generation. These systems should be able to provide real-time data on energy production, identify potential issues, and enable proactive maintenance and troubleshooting.
The vehicle is factory equipped by consumption monitor, while for the energy generations, an additional monitoring system should be added.
For the software part, there are already present many commercial and DIY solutions on the market, that can satisfy the required performance of the system. They are designed to work on a real estate, however with slight modifications and tuning, can perform properly on the vehicle too.
Among the hardware parts, I would like to mention 4 required sensors:

- Temperature
- Voltage
- Current
- Light

Since the integration of the solar panels is an auxiliary equipment, for this thesis scope, the output of this system will be transmitted to an additional monitor, responsible for the solar part of the vehicle. With the further advancement in use of the solar panels, the direct integration to the OEM control system will be the logical and consequent outcome for this project.

By addressing these aspects of structural and electrical integration, I will be able to ensure the seamless incorporation of CdTe solar panels onto public bus, maximizing their efficiency and minimizing any potential challenges or risks.

4.5 Environmental impact assessment

The time interval for the lifecycle of semi-transparent CdTe solar panels can vary depending on several factors, including the quality of materials, manufacturing processes, operating conditions, and maintenance practices. On average, CdTe solar panels have a lifespan of around 20 to 30 years. However, with proper maintenance and care, they can potentially exceed this range and continue to generate electricity effectively.
It's important to note that the degradation rate of CdTe solar panels tends to be relatively low compared to other photovoltaic technologies. CdTe panels have shown good stability and long-term performance in various studies and field applications. The panels may experience a gradual decrease in efficiency over time, but they can still maintain a significant portion of their initial power output throughout their lifecycle.
Proper installation, regular maintenance, and adherence to manufacturer's guidelines can help maximize the lifespan of semi-transparent CdTe solar panels.
So, the additional solar panels will serve for the whole lifecycle of the vehicle, considering also the probability of battery replacement and can be recycled together with the vehicle.

4.6 Social acceptance and public perception

Preliminary analysis reveals positive public perception towards solar-powered buses. It is a logical consequence of the modern trend, supporting renewable energy initiatives and perceived the integration of CdTe solar panels on buses as a step towards a greener and more sustainable public transportation system. The qualitative analysis further explored the underlying reasons for the positive perception, such as environmental consciousness, perceived benefits to air quality, and the visibility of solar panels promoting renewable energy awareness.
The results of the case study highlight the importance of social acceptance in the successful implementation of solar-powered public transportation. The positive public perception indicates a favorable attitude towards sustainable transport solutions and a willingness to embrace renewable energy technologies. However, challenges and concerns related to cost, reliability, and aesthetic considerations were also identified, emphasizing the need for effective communication, education, and addressing public concerns to further enhance social acceptance.

Chapter 5: Solar panels experimental comparison

After completing the comprehensive modeling of the bus, encompassing the dimensions of both the vehicle and solar panels, as well as addressing the challenges associated with integration and devising an overall system design, the focus shifts towards investigating the solar panels themselves. This chapter entails conducting practical experiments to evaluate different models of solar cells with the aim of identifying the most suitable solution for the intended application.

The experimental part is divided into 2 parts, the former one accounts for efficiency and establishes best possible electrical gain, while the latter one evaluates the real-world behavior of the panels.

5.1 Research methodology

Research Objective: To investigate the performance of thin semi-transparent CdTe solar panels on public transport vehicle, but positioning then vertically with inclination of 89°, with a focus on the impact of the glass transparency and panel composition.

Experimental Design:

- The testing will be divided into 2 subparts
- The first part will be on the test bench to compare the efficiency, passengers' comfort
- The latter one will be real world simulation, evaluating the possible energy gain during the working hours of the bus.

Test Parameters:

- the energy output
- efficiency
- angle of incidence
- temperature

Panel Installation:
Install the selected panels on a test bench, following proper mounting procedures and safety guidelines. Since all the panels will be mounted together on the wall, I could ensure the same environmental conditions for each panel type (e.g., solar exposure, tilt angle, illumination, temperature).

Data Collection: a monitoring systems to measure energy output, environmental conditions, and other variables of interest. Collecting data over a year to account for variations in weather and sunlight conditions.

5.2 Selection of panel types

For this part of the experiments, a vertical wall was created in order to support the 4 specimens and sensors, in order to compare the effect of the transparency level on the panel efficiency and passenger's comfort.
General expectations based on the transparency levels:

- **S1- 35% Transparency:** Provides a relatively high level of visible light transmission. Suitable for applications where maintaining good visibility and natural lighting is important, such as windows or skylights. Balances energy generation with visibility.
- **S2- 25% Transparency:** Offers a moderate level of visible light transmission. Suitable for various applications where a balance between energy generation and visibility is desired. Can provide both energy efficiency and some level of transparency.
- **S3- 20% Transparency:** Represents a lower level of visible light transmission. Suitable for applications where energy generation is a higher priority than visibility. May be used in settings where partial shading is acceptable.
- **S4- 5% Transparency:** Provides minimal visible light transmission, making it nearly opaque. Not suitable for my applications, but where maximum energy generation is the primary goal, and visibility is not a significant concern.

Figure 18 – Solar panel transparency comparison

Taking into account that the visual comfort considerations suggest minimum acceptable values for glazing transmittance is in range between 19% and 38%, the optimal solution for my problem should be the specimens 1,2 or 3. The last on is taken into account in order to evaluate the power gain order of difference between the transparent and opaque ones.

Specimens' specifications				
	S1	S2	S3	S4
Type	CdTe Thin-film based PV glazing			
Dimensions	15 cm x 15 cm			
Thickness	6 mm			
Composition	3 mm tempered glass– thin film			
Solar cell dimensions	11 cm x 11 cm			
Solar cell area	0.0121 m^2			
Weight	0.9 Kg			
Transparency	35%	25%	20%	5%
Solar cell ratio	61%	72.4 %	79.2 %	90.48 %
Output power	0.9 W	1 W	1.2 W	1.5 W
Operating voltage	7.5 V	8 V	8.5 V	9.5 V
Operating current	0.12 A	0.13 A	0.15 A	0.19 A
Open-circuit voltage	10.8 V	11.7 V	12.5 V	13.2 V
Short-circuit current	0.14 A	0.17 A	0.19 A	0.24 A

Figure 19 – Specimens' specification summary

5.3 Equipment

Equipment and Materials:

- Solar panel specimens
- Pyranometer (to measure solar irradiance)
- Current and voltage sensors
- Data logger
- Moving test bench

While the sensors do not require particular introduction, I would like to say some words regarding the data logger.

Due to necessity of standalone data recording, complexity and cost, the appropriate choice for this experiment was the data logger. It's worth noting that many modern data loggers offer both data logging and limited real-time monitoring capabilities.

A data logger is a standalone device designed to capture and record data from sensors over an extended period. It usually includes the following features:

1. Input channels:
   - My data logger has 16 multiple input channels to accommodate various sensor connections.
   - Each channel is capable of measuring and recording the voltage or current from the solar panel.
2. Memory and storage:
   - Data loggers have built-in memory or storage capacity to store the acquired data.
   - Stored information can be easily converted into MS Excel file.
3. Logging intervals and sample rates:
   - Data loggers allow you to configure the logging interval or sample rate, which determines the frequency at which measurements are taken.
   - Setting the logging interval of 1 minute, I was able to acquire all necessary data.

These sensors are connected to the input channels of the data logger, allowing the system to measure and record the current and voltage data from the solar panels.

5.4 Setup and configuration

The optical and electrical properties provide indoor sunlight with power generation. The impact of PV panels vertical orientation was studied by implementing outdoor experiments using a moving test bench.

In order to establish a performance assessment for all cells under the same conditions, an experimental setup had been built, positioning the specimens in a horizontal row one after another. A data acquisition and logging system had been used to gather data and save it in an excel sheet.

Because of the constraint of a fixed size of the available panels (20 X 20 cm^2) the enclosures had been designed with dimensions of 20 X 20 cm^2. It is worth mentioning that the active area of the solar cell is within the 10 X 10 cm^2.

Outdoor experiments were dedicated to the overall system energy evaluations in real weather. The evaluations included orientation aspects, not considering the light and shading disturbances.

1. Experimental Setup:
    - As a location for my experiment, I used my company's backyard, due to unobstructed access to sunlight.
    - The mounting was vertical, following the normal inclination of the bus windows
    - Connect the solar panels to the data logger, ensuring proper connections for measuring current and voltage.
    - Connect the pyranometer to measure solar irradiance.

2. Calibration:
    - Calibrate the sensors of the data logger to ensure accurate measurements. Follow the manufacturer's instructions and using a reference panel I was able to precisely tune the sensors.

3. Experimental Procedure:
    - Begin by rotating the test bench, positioning the panels under direct sunlight.
    - Initializing and configuring the data logger to record the current, voltage and irradiance.
    - Record the environmental conditions, such as ambient temperature and wind speed.
    - Start the data logger to initiate data recording.
    - Correct every hour the setup directions following the sun trajectory

5.5 Data collection

Data Collection:

- Measure and record the solar irradiance using the pyranometer at regular intervals (every minute) throughout the experiment.
- Simultaneously, measure and record the current and voltage output of the solar panel using the data logger.
- Take multiple readings for each parameter to account for any variations or fluctuations.

The IV curves for specimens used are presented in the figure below. The I-V curves reveal that the maximum power point (MPP) of S4 is the highest compared to others, which has the lowest value of MPP.
The curves have this shape, since they represent power gain during the duration of the typical working hours, starting from 8 AM till 6 PM.

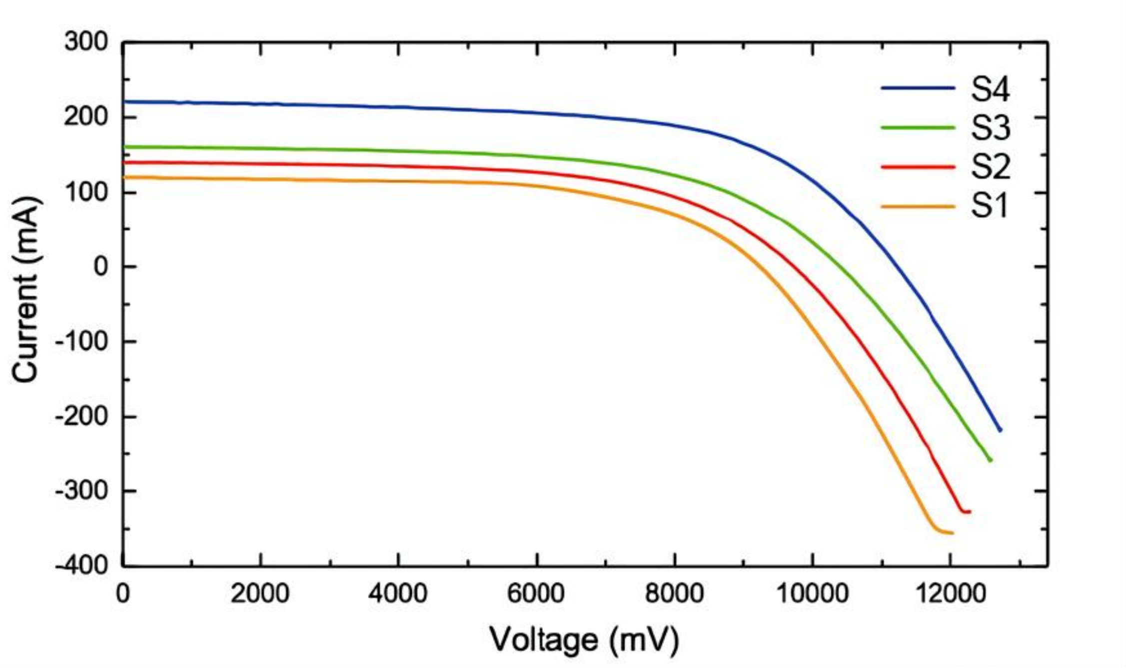

Figure 20 – The I-V curve of panels used in test

5.6 Data analysis and results

1. Calculation of Power and Energy:

- Calculate the instantaneous power output of the solar panel at each interval using the recorded voltage and current values (Power = Voltage x Current).
- Multiply the power output by the corresponding duration to obtain the energy produced per day.
- Get the average energy values over the entire duration of the experiment to calculate the total energy gained by the solar panel.

2. Data Analysis and Observations:

- Analyze the collected data, including solar irradiance, voltage, current, power, and energy.
- Observe the relationship between solar irradiance and energy generation.
- These results are average value of energy gain by solar panel in the best working conditions.

Electrical properties of the specimens				
	S1	**S2**	**S3**	**S4**
Transparency level (%)	35	25	20	5
Nominal Power (W)	0.9	0.98	1.19	1.48
Short Circuit Current (A)	0.14	0.17	0.19	0.24
Open Circuit Voltage (V)	10.78	11.68	12.47	13.2
Current at Maximum Power Point (A)	0.122	0.14	0.156	0.204
Voltage at Maximum Power Point (V)	8.34	8.46	9.084	9.936
Efficiency (%)	9.08	10.04	11.05	12.76
Max Power (W)	0.85	0.973	1.18	1.69
Energy per day, max (kWh)	0.013	0.014	0.018	0.025
Energy per day, min (kWh)	0.007	0.008	0.009	0.013
Average energy gain per day (kWh)	0.011	0.012	0.015	0.021
Average daily energy gain per m^2 (kWh*m^2)	**1.063**	**1.216**	**1.476**	**2.11**

Figure 21 – Average electrical properties of cells under best working conditions

The table above also shows the maximum and minimum energy gains per day, that were recorded on the 21 June and 21 December respectively. These dates can be explained by the summer and winter solstices. The summer solstice is an astronomical event that marks the longest day of the year and the start of summer in the Northern Hemisphere, while the winter one represents the shortest day.

Detailed results of specimens' capabilities are presented in the table above. The results confirmed initial expectations, that the efficiency and power generation were found to be inversely proportional to transmittance. The maximum efficiency and power generation for both orientations was registered for S4 whereas S1 showed the lowest efficiency and power generation.

However, these results are under best working conditions, and cannot be achieved during normal working conditions. These numbers will be used as a reference for further experiments.

Chapter 6: Real working conditions experimental simulation

After completing the comparison between solar panel specimens in the best working conditions, with test bench following the sun trajectory, the "real world" behavior of the solar panels was evaluated. The specimens were positioned on a moving object, having to deal with the light and shading disturbances. To completely analyze the behavior, the duration of data collection took more than a year of a time.

6.1 Research methodology

Research Objective: To investigate the energy performance of CdTe thin-film based panels under realistic weather and solar irradiance conditions, outdoor experimental setup was done, simulating public transport vehicles, with a focus on "real world" simulation of the working capability and durability.

Test Parameters:

- the energy output
- efficiency
- temperature
- durability
- shading effects.

Panel Installation:
For this part of the experiments, instead of using 4 different types of panels, 4 specimens of S3 cells with 20% transparency were implied. The panels were installed on 4 sides (2 sides, rooftop and rear) of the food delivery backpack, similar to the position of the windows of a public bus. With this positioning of the panels, I could ensure different environmental conditions for each panel type (e.g., solar exposure, tilt angle, illumination).
Depending on the position of the specimen, their nomenclature would be the following:

- Left side of the backpack – LHS3
- Right side – RHS3
- Rooftop – RFS3
- Rear, facing the road – RS3

Data Collection: a monitoring systems to measure energy output, environmental conditions. The output of the experiment was a sinusoidal signal for current and voltage. Collecting data over a year to account for variations in weather and sunlight conditions.

6.2 Equipment

Equipment and Materials:

- Solar panel specimens
- Current and voltage sensors
- Portable data logger
- Food delivery backpack (44x44x50cm)
- Rider

Figure 22 – Backpack with solar panel specimens

The sensors remain the same, while the data logger was changed to portable one, allowing the positioning in the food delivery backpack.

The data concerning the environmental conditions was recorded manually by rider.

These sensors are connected to the input channels of the data logger, allowing the system to measure and record the current and voltage data from the solar panels.

6.3 Setup and configuration

Control Variables: very random driving routes, speed, and operational conditions during testing, depending on the order and delivery addresses.

For better simulation of the process, the rider was using electric scooter, allowing the backpack stay mostly stable in the vertical position during the rides.
A data acquisition and logging system had been used to gather data and save it in an excel sheet.

As in the previous chapter, because of the constraint of a fixed size of the available panel (20 X 20 cm^2) the enclosures had been designed with dimensions of 20 X 20 cm^2. It is worth mentioning that the active area of the solar cell is within the 10 X 10 cm^2.

Worth to notice, that the mounting of the panels was done using different techniques. During the first trials the enclosures were mounted using the structural adhesive. Unfortunately, this method did not last long, so we had to change it during the experiments. Further solution was to knit the panels directly to the backpack, that showed optimal results and remained untouched till the end of the tests.

1. Experimental Setup:

    - As for location for my experiment, the working area for the human-powered riders is limited to the central areas of Turin, similar to public transportation network
    - The mounting was vertical, following the positioning of bus windows
    - Connect the solar panels to the data logger, ensuring proper connections for measuring current and voltage.
    - Position the data logger in order to avoid the unvoluntary damage.

2. Calibration:

    - Calibrate the sensors of the data logger to ensure accurate measurements. Follow the manufacturer's instructions and using a reference panel (data from the previous experiments) I was able to precisely tune the sensors.
    - Ensure stable data acquisition during rider movement

3. Experimental Procedure:
   - Rider turns on the data logger and ensures data acquisition
   - Record the date and working time slot period
   - Record the environmental conditions and ambient temperature
   - Start the food delivering service

The inclination was changing constantly in the order of ±10 deg. due to road imperfections, traveling routes and rider movements during turning.

6.4 Data collection

Data Collection:
- Measure and record the environmental conditions and time at the begging and the end of the working periods.
- Simultaneously, measure and record the current and voltage output of the solar panel using the data logger.
- Take multiple readings for each parameter to account for any variations or fluctuations.

It is important to highlight that data logging commenced as early as 8 AM, aligning with the working shifts of the rider. This approach ensured that the data collected accurately represented the solar panel's performance during the operational hours corresponding to the rider's working schedule.

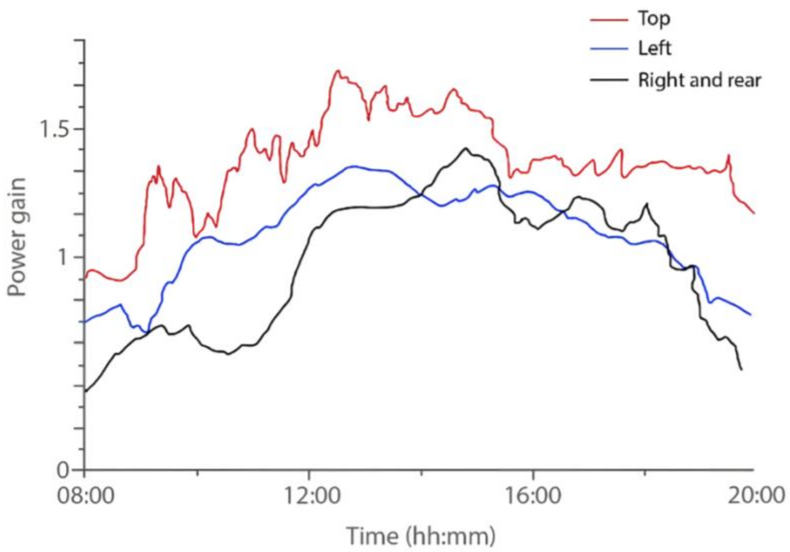

Figure 23 – Panels' daily performance

The graph above vividly illustrates the power gain of the solar panel system. The graph showcases a fluctuating pattern in the power gain, which is characteristic of solar energy systems. However, upon closer observation, a discernible correlation emerges: the power gain values generally align with the solar activity.

Figure 24 – Rider in the streets of Turin collecting data

Solar activity, influenced by factors such as the position of the sun, weather conditions, and time of day, significantly impacts the energy generation of the solar panel system. The fluctuating behavior in the power gain is a direct reflection of these changing solar dynamics. During periods of increased solar activity, the power gain tends to rise, whereas it dips during lower solar activity. This alignment with solar activity is a reassuring validation of the system's functionality.

6.5 Data analysis and results - body

The data collected in the preceding phase underwent a thorough process of simplification and comprehensive analysis. Employing the Root Mean Square (RMS) approach, an average value representing the power gain per hour was derived. It's worth noting that this value is varying depending on weather conditions, the specific day of the year, and the route taken by the driver during his operational hours. Following the solar irradiance and daylight duration variability, an average value for different season was evaluated.
The right and rear positioning of the PV cells showed almost identical result, with negligible difference between them, so in the future calculations I assume their power gain equal.
Unexpected outcome, was that the left side panel performed better than the right one.
This phenomenon, I suppose, can be explained by better exposure to sunrays, since the rider usually stay on the right side of the road, leading to higher exposure of the left side by non-obstructed light.

Right and rear panels				
	Spring	**Summer**	**Autumn**	**Winter**
Nominal Power (W)	0.89	0.98	0.89	0.80
Short Circuit Current (A)	0.14	0.16	0.14	0.13
Open Circuit Voltage (V)	9.07	9.98	9.07	8.16
Current at Maximum Power Point (A)	0.12	0.13	0.12	0.11
Voltage at Maximum Power Point (V)	6.69	7.36	6.69	6.02
Efficiency (%)	7.34	8.07	7.34	6.60
Max Power (W)	0.782	0.947	0.782	0.634
Energy per day, max (kWh)	0.010	0.014	0.009	0.006
Energy per day, min (kWh)	0.009	0.012	0.008	0.005
Average energy gain per day (kWh)	0.0103	0.0146	0.0095	0.0063
Average daily energy gain per m^2 (kWh*m^2)	**1.033**	**1.458**	**0.947**	**0.627**

Figure 25 – Electrical properties of right and rear cells

Left panel				
	Spring	**Summer**	**Autumn**	**Winter**
Nominal Power (W)	0.99	1.09	0.99	0.89
Short Circuit Current (A)	0.16	0.18	0.16	0.14

Open Circuit Voltage (V)	10.39	11.43	10.39	9.35
Current at Maximum Power Point (A)	0.13	0.14	0.13	0.12
Voltage at Maximum Power Point (V)	7.57	8.33	7.57	6.81
Efficiency (%)	8.23	9.05	8.23	7.41
Max Power (W)	0.984	1.191	0.984	0.797
Energy per day, max (kWh)	0.013	0.018	0.012	0.008
Energy per day, min (kWh)	0.011	0.015	0.010	0.006
Average energy gain per day (kWh)	0.0130	0.0183	0.0119	0.0079
Average daily energy gain per m^2 (kWh*m^2)	**1.299**	**1.834**	**1.191**	**0.789**

Figure 26 – Electrical properties of left panel cells

6.6 Data analysis and results - rooftop

Depending on the position of the panel the efficiency changed, with expected overall better performance obtained by the top one, rather than others. Even though for rooftop is out of the interest for this thesis, it would have been a big loss not to calculate the energy gain during on the streets experiments. For the experiments I used the same type of semi-transparent CdTe panel, as on the other parts of the vehicle.
The efficiency of the solar panel varied based on its placement, with notable distinctions in performance of the top panel, that exhibited a consistently superior performance compared to other positions. While the focus of this thesis is not primarily on rooftop installations, it was important to measure how much energy it could generate during on-road tests. It would have been a mistake not to check the rooftop's potential.

Rooftop, using semi-transparent CdTe panel				
	Spring	**Summer**	**Autumn**	**Winter**
Nominal Power (W)	1.09	1.19	1.09	0.98
Short Circuit Current (A)	0.18	0.19	0.18	0.16
Open Circuit Voltage (V)	11.09	12.20	11.09	9.98
Current at Maximum Power Point (A)	0.14	0.16	0.14	0.13
Voltage at Maximum Power Point (V)	8.17	8.99	8.17	7.36
Efficiency (%)	8.97	9.86	8.97	8.07
Max Power (W)	1.169	1.414	1.169	0.947
Energy per day, max (kWh)	0.015	0.021	0.014	0.009
Energy per day, min (kWh)	0.013	0.018	0.012	0.008

Average energy gain per day (kWh)	0.0154	0.0218	0.0141	0.0094
Average daily energy gain per m^2 (kWh*m^2)	**1.543**	**2.178**	**1.414**	**0.937**

Figure 27 – Electrical properties of rooftop semi-transparent CdTe solar cells

In the course of these experiments, the same type of semi-transparent CdTe panel were used all over the vehicle. This made sure observations were fair and I could accurately compare how the panel's position affected its efficiency.

However, in the context of a practical application, opting for non-transparent, high-efficiency CdTe panels would be the more suitable choice. This is primarily because the bus model under examination isn't outfitted with a panoramic sunroof, rendering the transparency aspect less critical. Instead, the emphasis shifts to maximizing energy output
Knowing the energy performance and applying the correction factors for semi-transparent panels, the expected energy output of high-efficiency panels was calculated.

Rooftop, using high-performance CdTe panel				
	Spring	**Summer**	**Autumn**	**Winter**
Nominal Power (W)	2.06	2.27	2.06	1.86
Short Circuit Current (A)	0.19	0.21	0.19	0.17
Open Circuit Voltage (V)	21.07	23.17	21.07	18.96
Current at Maximum Power Point (A)	0.16	0.17	0.16	0.14
Voltage at Maximum Power Point (V)	15.53	17.08	15.53	13.98
Efficiency (%)	17.03	18.74	17.03	15.33
Max Power (W)	2.443	2.956	2.443	1.979
Energy per day, max (kWh)	0.032	0.044	0.029	0.020
Energy per day, min (kWh)	0.027	0.038	0.024	0.016
Average energy gain per day (kWh)	0.0322	0.0455	0.0296	0.0196
Average daily energy gain per m^2 (kWh*m^2)	**3.224**	**4.552**	**2.956**	**1.959**

Figure 28 – Corrected electrical properties of rooftop solar cells

Chapter 7: Application of the experimental results

After studying how solar panels behave in different situations, the next step involves calculating how much power they can generate. The initial experiment shed light on the behavior of semi-transparent panels under optimal conditions, emphasizing the impact of inclination angles, in particular vertical positioning of the solar panels.
The next experiment involved collecting data while our setup moved through Turin, dealing with varying light and shadows. This real-world data helps us understand how the solar panels would perform on a moving public bus in the city.
By combining the results of these two experiments, we can estimate the solar power a public bus equipped with these panels could generate during its regular operations. This approach—from controlled experiments to real-world conditions—gives us a good estimate of the solar energy potential for sustainable public transportation.

7.1 Summary of the experiments

After carefully analyzing the outcomes of the initial experimental setup, a solar panel type with 20% transparency emerged as the optimal choice. This specific panel demonstrated a commendable daily energy gain per square meter, averaging at 1.476 kWh/m2. This value became the targeted output for the subsequent experiment, as it represented an efficient performance benchmark to strive for.
In the subsequent experiment, various sides of the solar panel were assessed to gauge their individual energy generation capabilities. The results exhibited a nuanced differentiation in the average daily energy gain per square meter for different sides of the panel:

- The top panel recorded an average daily energy gain of approximately **3.173 kWh/m2.**
- The left side showcased an average daily energy gain of around **1.278 kWh/m2.**
- Conversely, the right and rear sides exhibited a slightly lower average daily energy gain, quantified at approximately **1.016 kWh/m2.**

This insightful data not only highlighted the overall efficiency of the chosen solar panel but also provided a granular understanding of how energy generation varies across different panel positioning.

7.2 Performance Analysis - energy generation of the body panels

Utilizing the data, gained in the Chapter 6.5 and applying it on the glass area of the bus, I was able to calculate average daily power gain of the semi-transparent solar panels.
Remembering that, the glass area of the bus equals to:

- Left side – 14.94 m^2
- Right side – 12.46 m^2
- Rear side – 2.43 m^2

It's important to emphasize that in calculations, a correction factor of 10% was taken into account. This correction factor was applied to the final calculation, aiming to enhance the accuracy and ensure a more precise representation of the expected output from the entire solar panel system. By considering this correction factor, I aimed to align calculations more closely with real-world conditions and provide a more reliable estimate of the actual system performance.

Daily average power gain (kWh)				
	Spring	**Summer**	**Autumn**	**Winter**
Left side	17.1	24.1	15.7	10.4
Right side	11.3	16.0	10.4	6.9
Rear	2.2	3.1	2.0	1.3
Total (kWh)	**30.6**	**43.2**	**28.1**	**18.6**

Figure 29 – Adjusted daily average power gain

With declared power consumption of the vehicle of 91kWh/100km, the integration of solar panels can add in average 30km of range daily.

7.3 Performance Analysis - energy generation of the rooftop panels

When considering the rooftop area, the available space totals nearly 21 m², providing a substantial area for integrating high-efficiency solar panels. Moreover, the top panels benefit superior sun exposure due to their location, resulting in a higher energy output compared to panels on other sides.
During different seasons, the rooftop panels demonstrate remarkable power generation:

- Spring: 48.4 kWh
- Summer: 68.4 kWh
- Autumn: 44.3 kWh
- Winter: 29.4 kWh

These calculations provide a valuable insight: the power generated by the rooftop panels surpasses that of all the combined body panels by nearly 50%. This underlines the significant contribution that the rooftop integration can make to the overall energy output of the system.

One significant disadvantage is associated with the rooftop solar panels, that they are exposed to environmental elements such as dust, dirt, and other debris. Consequently, the solar panels on the roof require regular cleaning and maintenance routines, in order to ensure optimal performance.

7.4 Financial Analysis: Cost Estimates

In this chapter, the cost per square meter of the solar panels was solely observed, installation or any other extra expenses weren't taken into consideration. The goal is to understand how much the solar panels themselves cost for each square meter.
By focusing only on the solar panel cost, we get a clear view of the basic expenses related to the panels. This helps us understand the fundamental cost of the solar technology itself. However, it's important to remember that in real-world scenarios, we would need to consider all the costs involved, including installation and other additional expenses.

Cost estimation		
	Area (m^2)	**Cost per m^2 (€)**
Semi-transparent CdTe	30	120
Rooftop	21	95
Total	**51**	**5595**

Figure 30 – Solar panels cost estimation

The prices are average market costs per square meter for Mid.2023.

Chapter 8: Solar panel testing and safety regulations

When considering solar panel integration in public transport, ensuring compliance with safety regulations and maintaining emergency exit capabilities should always be a top priority. The second important issue to consider relates to misuse situations and solar panel safety regulations. Consequently, this chapter covers the topics concerning the Module Breakage Tests, electrical, structural and mechanical safety, fire safety measures and emergency measurements.

8.1 Importance of durability in solar panel performance

A Module Breakage Test, also known as a mechanical or impact test, is a critical assessment used in the solar panel industry to evaluate the durability and resilience of photovoltaic (PV) modules when subjected to various types of mechanical stress or impact. This test helps assess the panel's ability to withstand environmental conditions, handling during transportation and installation, and other potential sources of physical damage. In my case it will determine the safety factor in case of passenger misuse and vandalism situations.

Here are the key aspects of a Module Breakage Test:

Objective: The primary goal of a Module Breakage Test is to determine whether a solar panel can withstand mechanical stresses and impacts without sustaining significant damage that could affect its performance or safety.

Types of Mechanical Stress: The test can involve different types of mechanical stress or impact scenarios, including:

1. **Hail Impact Test:** Panels are exposed to simulated hailstones of various sizes and speeds to assess their ability to withstand hailstorms, a common environmental risk.
2. **Static Load Test:** This evaluates the panel's resistance to static forces, such as the weight of snow or debris that might accumulate on it.
3. **Dynamic Mechanical Load Test:** Panels may be subjected to dynamic loads, mimicking conditions such as high winds or structural movement in buildings.
4. **Drop Test:** Panels are dropped from a specified height to simulate the effects of mishandling or accidents during transportation or installation.

For the purpose of this thesis, I'm mainly interested in the first two tests, since the windows should withstand the occasional impacts during the lifecycle, in addition to the structural stresses supported by the windows.

8.2 Module breakage tests overview

Testing Standards: Standards from organizations like IEC and ISO, e.g., IEC 61215 and IEC 61646, provide guidelines for Module Breakage Tests.
Test Procedures: These tests involve subjecting a solar panel to defined mechanical stresses, assessing its performance, structural integrity, and electrical properties before and after. Parameters include power output, insulation resistance, and visual inspection for damage.
Pass/Fail Criteria: Results are matched against predefined criteria in the testing standards. Passing implies durability and suitability for harsh environments.
Importance: Critical for solar panel reliability and safety, especially in extreme weather-prone areas, revealing design weaknesses and prompting enhancements.
Certification: Successful tests may lead to industry or regulatory certifications, assuring product quality and reliability to consumers and installers.

Figure 31 – Module breakage tester

(The solar panel is hit by leather impactor wrapped with tape and a weight of 45.5kg)

8.3 Safety considerations

What concerned the safety requirements, the integration of solar panels necessitates careful attention to the subsequent critical aspects:

Electrical Safety

It is a critical aspect when integrating solar panels into public transport. It encompasses ensuring the safe and proper functioning of all electrical components within the solar panel system.
This topic was described in the Chapter 4.4 and does not require additional coverage.

Structural and Mechanical Safety

The focus here is on the structural integrity of the solar panel installations on the public transport. Since mounting of the panels follows the OEM method of affixing, using the structural adhesive, they should not affect the initial structural behavior of the vehicle. Additionally, the laminated panels will only increase the mechanical properties of the outer glass shell of the bus, so it can withstand mechanical stresses such as wind loads, vibrations during transit, or potential impacts.

What concerned the structural safety, that includes considerations for the vehicle's overall stability and weight distribution to prevent any adverse effects on handling, the weight increase of the vehicle is nearly 30 kg per side, that can be considered irrelevant with respect to overall bus mass.

Fire Safety Measures

Fire safety is of utmost importance, especially when integrating any additional components like solar panels into a vehicle. However, being an electrical public transportation vehicle, it inherently equipped with fire safety measures. There is no requirement in additional equipment, since the solar panels are made of laminated glass and work with quiet low currents, making them safe from this point of view, while for the rest of the system, I can rely on OEM safety features.

Emergency measurements

Emergency response procedures are essential to swiftly address any unforeseen incidents. This includes developing and communicating a clear set of actions to be taken during emergencies, ensuring everyone knows their roles and responsibilities.
Windows play an essential role as vital emergency exits across a range of transportation modes, buses being no exception. However, replacing all bus windows with solar panels may obstruct passengers' ability to utilize them as emergency exits, presenting a notable safety concern.
This topic will be explored further in the next chapter.

Incorporating and meticulously addressing these aspects within the safety regulations chapter would contribute to a comprehensive understanding of the safety measures essential for the integration of solar panels on public transport, ultimately promoting a secure and reliable system, significantly reducing the risk of hazards within the public transport system.

8.4 Emergency measurements

Windows serve as crucial emergency exits in various transportation vehicles, including buses. If all the bus windows are substituted with solar panels, it could impede passengers' ability to use them as emergency exits, posing a significant safety concern.

The reason is that the semi-transparent solar panels are made in the similar way to laminated glass, technically having solar cells in between of 3mm thick glass, holding them together. The interlayer will hold the shards in place, in case the glass break, providing a safe double-layered design.

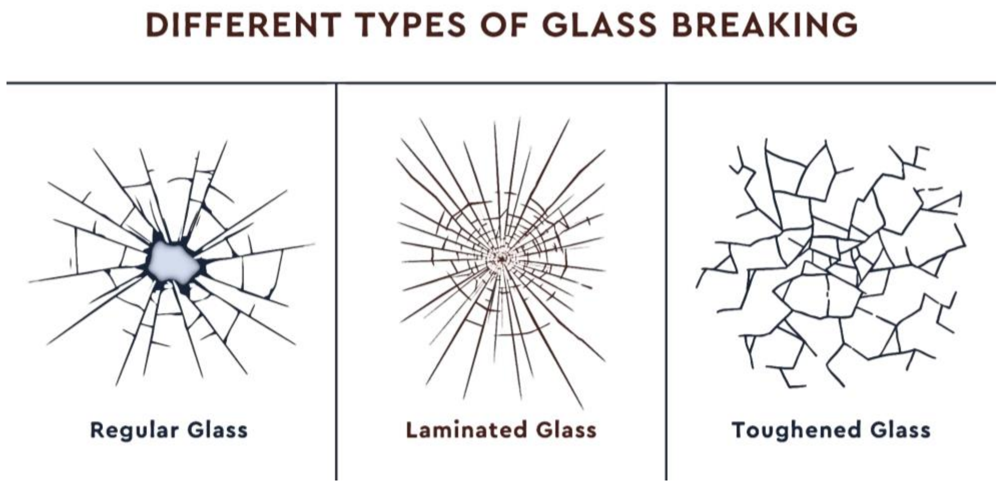

Figure 32 – Different types of glass breaking

The OEM tempered glass shows completely different behavior, it is specially treated so that it will break into small, blunt pieces under pressure, making it much safer than shards of normal glass. This is achieved by heating regular glass at high temperatures (650°C) and then cooling very quickly. This process makes it tougher (hence the name) and up to 400% or 500% more resistant to heat and shock than ordinary glass.
The aim of the toughening process is to primarily improve the structural durability and thermal strength of the glass, in turn increasing its resilience and ability to withstand heat.

Incorporating safety measures that preserve or provide alternative emergency exits is essential in such cases. Options could include implementing breakable panels or designated emergency exit points equipped with safety mechanisms that allow for quick and safe evacuation during emergencies.
When considering solar panel integration in public transport, ensuring compliance with safety regulations and maintaining emergency exit capabilities should always be a top priority.

8.5 Conclusion

In essence, finding a balance between durability and safety is crucial, particularly in emergency situations where quick glass breakage is necessary for escape. This balance entails further research this topic, by installing the solar panels into various transportation vehicles, without compromising safety and emergency exit capabilities for people.
At the first glance, various possibilities come to light, each necessitating careful consideration:

1. Implementation of breakable panels: One of the primary considerations involves the implementation of breakable panels within the solar panel structure. These panels would be designed to break under specific stress or pressure, allowing for a swift and uncomplicated exit during emergencies. This approach requires meticulous engineering to determine the exact threshold at which the panels should break, ensuring that they remain intact during regular operations while readily yielding to pressure in urgent situations.

2. Study of alternative emergency exit points: Another avenue for exploration revolves around the identification and assessment of alternative emergency exit points within the solar panel coverage area. This entails a comprehensive study of the vehicle's design to pinpoint areas where additional or modified emergency exits could be established without compromising the structural integrity of the transport. These exit points could be strategically positioned to ensure convenient and safe evacuation for passengers during emergency situations.

3. Design of safety mechanisms: Furthermore, a critical consideration is the design and integration of safety mechanisms that facilitate rapid and secure evacuation in emergency scenarios. These mechanisms could range from automated systems that rapidly retract or shift solar panels to designated safe zones or mechanisms that facilitate quick removal or detachment of solar panels, creating clear exit pathways for passengers.

The combination of above-mentioned options could enforce the idea of substituting the toughened glass by semi-transparent solar panels in the electrical transportation vehicles.

Chapter 9: Conclusion

In this section, a conclusion summarizing the key findings and contributions, using the insights and data acquired during the research will be provided. The outcome covers the power gain, achieved by integration of solar panel on public transport and improvements in passengers' comfort level.

9.1 Key findings

The research demonstrated that integrating semi-transparent CdTe solar panels onto public transport, for the scope of this thesis, electric buses, offers a promising avenue to harness solar energy. Different transparency levels were evaluated, showcasing varying energy gains and emphasizing the importance of a balanced approach considering both efficiency and translucency.

In the subsequent phase of this study, an exploration of the practical behavior of the solar panels in real-world conditions was conducted. The specimens were placed on a moving object, simulating their application on electric buses, thereby having to work in shifting light conditions and intermittent shading.
The duration of data collection took over a year, since it was important to evaluate the performance of the panels across different seasons and varying environmental conditions.

Daily average power gain (kWh)				
	Spring	**Summer**	**Autumn**	**Winter**
Left side	17.1	24.1	15.7	10.4
Right side	11.3	16.0	10.4	6.9
Rear	2.2	3.1	2.0	1.3
Body subtotal	**30.6**	**43.2**	**28.1**	**18.6**
Rooftop	**48.4**	**68.4**	**44.3**	**29.4**
Total (kWh)	**79.0**	**111.5**	**72.4**	**48.0**

Figure 33 – Daily average power gain per season

After analyzing the data, it is recommended to adopt a hybrid approach, integrating solar panels both on the rooftop and sides. This strategy maximizes energy generation and ensures robustness against shading effects.

It worth to mention, that establishing regular maintenance protocols is crucial, particularly for rooftop installations. Implementing automated cleaning systems can mitigate the negative effects of dirt accumulation and enhance the long-term efficiency of the solar panels.

The last, but not least, the solar panels positively affect passengers' comfort level, through superior sound dampening. Moreover, the 20% semi-transparent design of these panels contributes to reduction in the transmission of heat and UV radiation into the passenger compartment, leading to improved thermal comfort for the occupants.

9.2 Future possibilities and applications

Future research should focus on real-world implementations and larger-scale deployments to validate the theoretical findings of this study.

Additional studies concerning emergency situations, where quick glass breakage is necessary for escape are welcomed. This balance entails further research this topic, by installing the solar panels into various transportation vehicles, without compromising safety and emergency exit capabilities for people.

Last, but certainly not least, advancements in semi-transparent CdTe solar panels, resulting in heightened efficiency, would not only be advantageous but also enhance the appeal of solar panels for automotive manufacturers.

9.3 Conclusion

This thesis contributes to the field by providing valuable insights into the integration of CdTe solar panels on public transport. The findings present a foundation for future advancements in solar technology integration and its applications in sustainable public transportation.

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