Solar PV Powered Air Conditioning unit for a train passenger coach

By

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The objective of the present work is to design and select an air conditioning unit for a train coach using solar energy as the only source of energy, instead of the conventional system which is powered by a diesel generator.

The work is based on the estimation of air conditioning power consumption during 10 hours. An extensive study was done on calculating coach cooling load and sizing a suitable PV system.

Two options were considered: the first one was to use an alternating current PV system and the second one was to use a direct current PV system. Then an economical feasibility study was conducted to compare between the two systems and to study the overall economy of the proposed solar air conditioning unit. The first option was found to be the most economically feasible.
المستخلص

الغرض من هذا البحث هو تصميم واختبار وحدة تبريد لمقصورة ركاب في قطار باستخدام الطاقة الشمسية كمصدر وحيد للطاقة كبديل عن مولد الدiesel المستخدم حالياً، وذلك عن طريق استخدام الوان الطاقة الشمسية.

اعتمدت الدراسة على حساب استهلاك مكيف الهواء للطاقة لذلك اجريت حسابات مكثفة لحساب حمل التبريد في المقصورة واختيار نظام الوان شمسي مناسب.

أخذ خيارات بين الاعتبار هما: الأول هو استخدام وحدة تبريد تعمل عن طريق تيار متردد والثاني استخدام وحدة تبريد تعمل عن طريق تيار مباشر ثم أقيمت دراسة جدوى للمقارنة بين الخيارين ودراسة مدى اقتصادية وحدة تبريد تعمل بالطاقة الشمسية ووجد ان الخيار الأول هو الأقل تكلفه كليه.
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1.1 Introduction:

Every hour the sun beams onto Earth more than enough energy to satisfy global energy needs for an entire year. Solar energy is the technology used to harness the sun's energy and make it useable. Today, the technology produces less than one tenth of one percent of global energy demand. [1]

Figure 1.1 world irradiance [2]

Many people are familiar with so-called photovoltaic cells, or solar panels, found on things like spacecraft, rooftops, and handheld calculators.

The cells are made of semiconductor materials like those found in computer chips. When sunlight hits the cells, it knocks electrons loose from their atoms. As the electrons flow through the cell, they generate electricity.

By the end of 2014, cumulative photovoltaic capacity reached at least 178 gigawatts (GW), sufficient to supply 1 percent of global electricity demands. Solar now contributes 7.9 percent and 7.0 percent
to the respective annual domestic consumption in Italy and Germany. For 2015, worldwide deployment of about 55 GW is being forecasted, and installed capacity is projected to more than double or even triple beyond 500 GW between now and 202. By 2050, solar power is anticipated to become the world's largest source of electricity.

On a much larger scale, solar thermal power plants employ various techniques to concentrate the sun's energy as a heat source. The heat is then used to boil water to drive a steam turbine that generates electricity in much the same fashion as coal and nuclear power plants, supplying electricity for thousands of people.

In one technique, long troughs of U-shaped mirrors focus sunlight on a pipe of oil that runs through the middle. The hot oil then boils water for electricity generation.

Another technique uses moveable mirrors to focus the sun's rays on a collector tower, where a receiver sits. Molten salt flowing through the receiver is heated to run a generator.

Other solar technologies are passive. For example, big windows placed on the sunny side of a building allow sunlight to heat-absorbent materials on the floor and walls. These surfaces then release the heat at night to keep the building warm. Similarly, absorbent plates on a roof can heat liquid in tubes that supply a house with hot water; the figure below will give us a general view about solar thermal growth.

Solar energy is lauded as an inexhaustible fuel source that is pollution and often noise free. The technology is also versatile. For example, solar cells generate energy for far-out places like satellites in Earth orbit and cabins deep in the Rocky Mountains as easily as they can power downtown buildings and futuristic cars.
But solar energy doesn't work at night without a storage device such as a battery, and cloudy weather can make the technology unreliable during the day. Solar technologies are also very expensive and require a lot of land area to collect the sun's energy at rates useful to lots of people.

Despite the drawbacks, solar energy use has surged at about 20 percent a year over the past 15 years, thanks to rapidly falling prices and gains in efficiency. Japan, Germany, and the United States are major markets for solar cells. With tax incentives, solar electricity can often pay for itself in five to ten years.

By 2050, solar power is anticipated to become the world's largest source of electricity, with solar photovoltaic’s and concentrated solar power contributing 16 and 11 percent, respectively. This will require PV capacity to grow to 4,600 GW, of which more than half is forecasted to be deployed in China and India, figure below show the world installed capacity for solar power at 2011.

1.2 The objectives of the study:

This study aims at:

- Replace the conventional diesel generator set by PV solar system to power the air conditioning unit in a train passenger coach.
- Conducting a feasibility study of using PV energy (AC and DC systems) in railway coaches.

1.3 Importance of study:

Sudan railways uncounted a lot of problems due to the economic blockade which caused several complexities in import and export of products, spare parts and experts.
Using solar energy will decrease the demand of fossil fuel in this field and CO2 emission moreover we can achieve some independence in railway industry. Sudan enjoys considerable amount of solar energy that can be utilized as can be seen in figure [1,2] which present the solar irradiance falling on Sudan.

Figure 1.2 solar irradiance in Sudan [3]
CHAPTER 2

STUDIES AND PV TECHNOLOGIES

2.1 Introduction:
This chapter gives a review and broad information about applications of solar energy (PV) in trailed trains in some countries worldwide.

At this chapter PV concepts, components and systems will be explained.

2.2 Previous studies:

2.2.1 Indian Railways Get Promising Results From Solar Powered Coach:

Indian Railways (IR) consumed over 17.5 billion kWh of electricity during 2013–14. this corresponds to about 4000 MW — which is almost 1.8% of India’s power generation capacity.

IR is the country’s single largest high speed diesel (HSD) guzzler. In 2012-13, two-thirds of IR’s fuel bill was consumed by HSD, the remaining being spent for electricity. Indian Railways plans 1 GW solar power capacity.

The Integral Coach Factory of IR had announced a project in association with the Indian Institute of Technology Madras to design coaches that will draw power from the sun for interior lighting and cooling.[4]

Figure 2.1 Indian solar powered coach [4]
As a pilot project, one non-air-conditioned coach of Rewari-Sitapur passenger train was fitted with solar panels on the rooftop. The panels have been generating 17 kWh of electricity every day, which has been used for lighting load.

The cost of fitting these PV panels on a coach is estimated to be ₹390k (~$6,095). Given that the coach is powered from a diesel-based electric generator, the subsidy-free-payback can be as low as 4 to 5 years.

According to reports, a train using solar power can reduce diesel consumption by up to 90,000 liters per year and also bring down the carbon dioxide emission by over 200 tones.

2.2.2 First solar-powered train in Europe:

In June 2011, the first solar-powered high-speed international train left Amsterdam bound for Paris. The train plugs into a solar energy source fitted along the line.[5]

Figure 2.2 Europe train path [5]
The roof of the 2.5-mile tunnel crossing from Antwerp, in northern Belgium, is fitted with 16,000 solar panels that produce about 3,300 megawatts per hour of electricity, or the average annual consumption of nearly 1,000 families. They will not only power the high-speed rail, but also support inter-city trains while providing enough electricity to charge the train station.

2.2.3 Vili Solar Train:

Europe's first train powered entirely by its own solar panels, the Vili was recently launched in Hungary to carry passengers from Kiralyret and Kismaros, a scenic route not far from Budapest. This solar train is particularly impressive because it carries a cabin full of passengers — a task not required of many lightweight solar vehicles.[6]

![Figure 2.3 Vili solar train [6]](image)

The train's maximum speed of around 15 miles per hour means it's not ideal for efficient travel, but it's perfect for sightseeing.

2.2.4 220MPH Solar-Powered Bullet Train on Arizona Horizon:

Travelers going from Tucson to Phoenix may soon be blazing across the desert in speeding solar bullet trains propelled by the sun’s rays. Hot on the heels of President Obama’s plan for High Speed Rail in the US comes the news that Arizona-based Solar Bullet LLC is proposing a new 220mph bullet train that will be entirely powered by the sun and will make the trip in 30 minutes flat.[7]
Although the project is still in the very early stages of development, the company is hopeful it can start operating by 2018.

Initially, trains would run on two tracks reserved for the direct route between Tucson and Phoenix. Eventually, though, four additional tracks would be built to extend the route north and south and take in additional stops, including Chandler, Maricopa, Casa Grande, Eloy, Red Rock and Marana. The system would need 110 megawatts of electricity to run, which would be generated by overhead solar panels mounted above the tracks, making use of the Arizona's abundant sunshine.

"The system will dramatically reduce their dependence on imported oil and at the same time, minimize greenhouse gas emissions. To do this, all the necessary technology and equipment are currently available in Europe, Asia and Arizona. We look for this innovative system and our new MotionSolar Technology to give Arizona a tourism, economic, employment and technological edge. However the plan is not without its critics, not least for its huge price tag. The first phase is expected to cost about USD$27 billion.

2.2.5 Solar photovoltaic (PV) electricity to feed train depots starting from 2016 in Singapore:

Singapore, May 11th, 2015 / Phoenix Solar Pte Ltd, the Singapore based subsidiary of Phoenix Solar AG (ISIN DE000A0BVU93), an
international photovoltaic system integrator listed on the Prime Standard of the Frankfurt Stock Exchange, has been awarded the construction of 1.96 MWp of rooftop PV systems at the Tuas and Gali Batu train depots in Singapore.

The Land Transport Authority (LTA) is responsible for planning and development of Singapore’s land transport infrastructure. Achieving cleaner and greener transport is one of its priorities, as well as reducing the environmental impact of its business activities. Generating clean electricity for train depot operations is a significant step in the right direction.

In August 2014, LTA called for a competitive tender to design, supply and install 1.96MWp of grid-tie PV capacity on two new train depots - Tuas and Gali Batu. The project was awarded to Phoenix Solar after evaluating tenderers according to their quality proposals as well as pricing.

Upon completion, the PV system, consisting of 7’536 REC solar modules and 4 central inverters from SMA, are expected to generate over 2.2 million kWh of solar electricity annually. This is enough to offset over 1’100 metric tones per year of CO2 from gas fired power plants. As part of the contract, Phoenix Solar will also perform O&M (operations and maintenance) and monitor the performance of the PV system for an initial period of one year.

This project dovetails nicely with the Singapore Government’s plans to promote renewable energy using solar PV energy for public sector projects. Singapore has enough space to accommodate 6GWp of solar PV, which could in theory generate 7.5 TWh of electricity each year, or approximately 17% of Singapore’s current electricity demand. “Looking ahead, we expect PV to cover more industrial depots, warehouses, schools and government facilities” said Christophe Inglin, Managing Director of Phoenix Solar Pte Ltd. “The installations will not only provide environmental benefits but also commercial
returns, as PV today is a commercially viable complement to conventional energy in Singapore” continued Inglin.

With the addition of the two LTA PV systems, Phoenix Solar Pte Ltd boasts 8 rooftop installations in the MW range, bringing its rooftop portfolio to over 19 MWp, many of them award-winning projects.

Tim P. Ryan, Chief Executive Officer of Phoenix Solar AG, stated: "This new high-profile project underscores the strong positioning of Phoenix Solar in South East Asia. As in other regions around the globe, here too we enjoy a solid reputation for the design and execution of high-quality, high-output solar PV systems, providing a strong base for further growth.

2.3 PV Technology:

2.3.1 Solar Cell:

A solar cell or photovoltaic cell is a device that converts solar energy into electricity by the photovoltaic effect. It is very widely used in space application because it allows a clean and long-duration source of energy requiring almost no maintenance. Solar cells are composed of various semi conducting materials, constituting one or more layers. Silicon is very often used as it is the second most abundant element in Earth’s crust and thus inexpensive. For this reason, this material will be considered in the further explanations that are also valid for other types of semiconductors.[8]

Figure 2.5 PV cell [9]
2.3.2 Working Principles:

In figure 2.5, a simple silicon solar cell is represented with two doped semiconductors layers, p-type and n-type.

When the sunlight strikes the solar cell surface the cell creates charge carriers as electrons and holes. The internal field produced by junction separates some of the positive charges (holes) from the negative charges (electrons).

The holes are swept into the positive or p-layer and the electrons are swept into the negative or n-layer. When a circuit is made, the free electrons have to pass through the load to recombine with the positive holes; current can be produced from the cells under illumination.

Figure 2.6 silicon solar cell[10]

2.3.3 Solar Irradiance:

The energy coming from the sun depends on the wavelength, leading to the solar spectrum represented in figure.2.7 The reference solar
spectral irradiance AM0 (Air Mass 0) represents the irradiance at the top of the atmosphere with a total energy of 1353 W/m². At sea level, it is referred as AM1.5 and the total energy equals 1000 W/m².

Figure 2.7 solar spectrum [11]

An ideal and perfect solar cell that would cover the entire spectrum and convert all this energy into electricity would have an efficiency of 100 %. In reality, depending on the semiconductors used, only a part of this spectrum is covered.

In addition to the direct irradiance, we also have to consider the diffuse irradiance, which is predominant on a cloudy day, and the reflected irradiance.

Reflected irradiance is dependent on the albedo, which is a measure of the reflectivity of the Earth’s surface. Fresh snow has an albedo of around 80 %, desert sand 40% and grass between 5% and 30 %.
2.3.4 Some types of now days Applications:

Solar energy is used today in a variety of ways. Probably because today, more and more people understand the advantages of solar energy as our solar technology increases and the cost of fossil fuels rises. Solar energy systems today can now use to power homes, cities, cars, airplanes, air conditioning, heating, lighting, Agriculture, horticulture, etc.
2.3.5 Types of Solar Cells:

There exist various types of photovoltaic cells that can be sorted according to the type of material, the fabrication process, substrate, etc. The objective here is only to give a short and non-exhaustive overview of the existing types and the figure below explain the different types of PV cells.

![PV Cell Materials Diagram]

**SOURCE:** IPCC (2011), “SPECIAL REPORT ON RENEWABLE ENERGY”

Figure 2.10 Types of PV cells [14]

The most widely used type of material is silicon, because of its abundance and low cost. We can distinguish three types of *silicon solar cells* according to the type of crystal:

- Mono crystalline, for which absolutely pure semi conducting material is used which gives a high level of efficiency but at a high cost.
- Poly crystalline composed of crystal structures of varying sizes. The manufacturing process is more cost efficient but leads to less efficient solar cells.
• Amorphous (or thin-layer cell) where a silicon film is deposited on glass or another substrate material, even flexible. The thickness of this layer is less than 1 μm, thus the production costs are very low, but the efficiency is poor as well. However, other materials can be used as well like elements from groups’ three to five of the periodic table of the elements to produce compound solar cells.

These include gallium arsenide, copper indium dieseline, cadmium Telluride, etc. These cells are more expensive to produce, but lead to higher efficiency.

We can also mention the polymer solar cells made of organic material and the dye sensitized solar cells that are very promising technologies because they are inexpensive to fabricate. However, these technologies suffer from unstable efficiency problems that still must be solved and are not yet viable for industry.

In fact, the most efficient solar cells are of a stack of individual single junction cells in descending order of band gap. The top cell captures high energy photons and passes the rest on to lower-band gap cells. These multi junction cells can then convert a wider part of the solar spectrum leading to a high efficiency that goes up to 40 %. Figure [2.11] shows the best efficiencies obtained for various solar cell technologies.
At present, crystalline silicon semiconductors are the most common commercial type of PV cell (with a market share of 85-90%), although thin-film cells (10-15% market share) are beginning to challenge their dominance. Silicon semiconductors benefit from a higher efficiency (14-20%) and have a longer lifespan than other technologies, but lower-efficiency (4-17%) thin-film technology is cheaper. Emerging non-silicon organic technology has the advantage of not requiring rare materials, which brings down costs dramatically, at the expense of efficiency (5%+). Concentrated PV (CPV), which uses mirrors or lenses to concentrate and focus solar radiation on high-efficiency cells, is an alternative to concentrating solar power (CSP), but requires better solar irradiance and is, at present, far less common.

As the technology is highly modular, solar PV is well suited to distributed generation, either off-grid or grid-connected. The PV market is thus often viewed in terms of its four end-uses: residential on individual buildings; commercial/industrial; utility scale requiring...
1 MW or more; and off-grid supply for remote communities or telecommunications facilities.

Despite significant growth in installed capacity in the past 7 years, of 51%, generation is still limited due to a poor load factor.

Solar PV was the past decade’s fastest-growing renewable technology. Installed capacity rose from a negligible level in the early 2000s to more than 96 GW at the end of 2012. Solar PV capacity is expected more than to triple to 230 GW by 2017, with China taking over as market leader ahead of Germany and the US. At the same time, PV generation is likely to grow even faster, as a result of development in sunnier countries, which will increase the average load factor from 12% at present to almost 14% by 2017 [16].

Figure 2.12 solar PV world capacity (2005-2022) [16]
2.3.6 Types of PV systems:

PV systems can be very simple, consisting of just a PV module and load, as in the direct powering of a water pump motor, which only needs to operate when the sun shines. However, when for example a whole house should be powered, the system must be operational day and night. It also may have to feed both AC and DC loads, have reserve power and may even include a back-up generator. Depending on the system configuration, we can distinguish three main types of PV systems:

1- Stand-alone
2- grid-connected
3- hybrid system

The basic PV system principles and elements remain the same. Systems are adapted to meet particular requirements by varying the type and quantity of the basic elements. A modular system design allows easy expansion, when power demands change.

1- Stand-alone systems:

Stand-alone systems rely on solar power only. These systems can consist of the PV modules and a load only or they can include batteries for energy storage. When using batteries charge regulators are included, which switch off the PV modules when batteries are fully charged, and may switch off the load to prevent the batteries from being discharged below a certain limit.

The batteries must have enough capacity to store the energy produced during the day to be used at night and during periods of poor weather.

Figure 2.13 shows schematically examples of stand-alone systems; (a) a simple DC PV system without a battery and
Figure 2.13 stand-alone system without battery[17]

(b) A large PV system with both DC and AC loads.

Figure 2.14 PV system using batteries with AC and DC load[17]
2- Grid-connected systems:

Grid-connected PV systems have become increasingly popular for building integrated applications.

As illustrated in Fig. 2.18, they are connected to the grid via inverters, which convert the DC power into AC electricity. In small systems as they are installed in residential homes, the inverter is connected to the distribution board, from where the PV-generated power is transferred into the electricity grid or to AC appliances in the house. These systems do not require batteries, since they are connected to the grid, which acts as a buffer into that an oversupply of PV electricity is transported while the grid also supplies the house with electricity in times of insufficient PV power generation.

Large PV fields act as power stations from that all the generated PV electricity is directly transported to the electricity grid. They can reach peak powers of up to several hundreds of MWp.

Figure 2.15 on grid PV system[17]
3- Hybrid systems:

Hybrid systems consist of combination of PV modules and a complementary method of electricity generation such as a diesel, gas or wind generator.
A schematic of a hybrid system shown in Fig. 2.19. In order to optimize the different methods of electricity generation, hybrid systems typically require more sophisticated controls than stand-alone or grid-connected PV systems.
For example, in the case of a PV/diesel system, the diesel engine must be started when the battery reaches a given discharge level and stopped again when battery reaches an adequate state of charge. The back-up generator can be used to recharge batteries only or to supply the load as well.

![Figure 2.16 hybrid power generation system](image)

2.3.7 Components of a PV system:

A solar cell can convert the energy contained in the solar radiation into electrical energy. Due to the limited size of the solar cell it only
delivers a limited amount of power under fixed current-voltage conditions that are not practical for most applications. In order to use solar electricity for practical devices, which require a particular voltage and/or current for their operation, a number of solar cells have to be connected together to form a solar panel, also called a PV module.

For large-scale generation of solar electricity solar panels are connected together into a solar array.

Although, the solar panels are the heart of a PV system, many other components are required for a working system that we already discussed very briefly above. Together, these components are called the Balance of System (BOS).

Which components are required depends on whether the system is connected to the electricity grid or whether it is designed as a stand-alone system.

The most important components belonging to the BOS are:

- A mounting structure is used to fix the modules and to direct them towards the sun.
- Energy storage is a vital part of stand-alone systems because it assures that the system can deliver electricity during the night and in periods of bad weather. Usually, batteries are used as energy storage units.

- DC-DC converters are used to convert the module output, which will have a variable voltage depending on the time of the day and the weather conditions, to a fixed voltage output that e. g. can be used to charge a battery or that is used as input for an inverter in a grid-connected system.

- Inverters or DC-AC converters are used in grid connected systems to convert the DC electricity originating from the PV modules into AC electricity that can be fed into the electricity grid.
• Cables are used to connect the different components of the PV system with each other and to the electrical load. It is important to choose cables of sufficient thickness in order to minimize resistive losses.
Even though not a part of the PV system itself, the electric load, i.e. all the electric appliances that are connected to it have to be taken into account during the planning phase. Further, it has to be considered whether the loads are AC or DC loads[17].

2.4 Energy Storage:

When the energy production is not constant and continuous, a good energy storage method is necessary.
We can list many different ways to store energy:
• Chemical (hydrogen, bio fuels)
• Electrochemical (batteries, fuel cells)
• Electrical (capacitor, super capacitor, superconducting magnetic energy storage or SMES)
• Mechanical (compressed air, flywheel)
• Thermal
These different technologies coexist because their characteristics make them attractive to different applications.
From a user point of view, the main selection criteria are the energy and power density, the response time, the lifetime, the efficiency and of course the costs.
In the case of a solar train, the gravimetric energy density in Wh/kg, also called specific energy, and the peak power are the most crucial parameters that determine the choice of the energy storage method.
The volumetric energy density will of course also have an influence on the fuselage size, this volume plays a minor role on the power required compared to the weight. In the present case, electrochemical batteries and fuel cells are the two best candidates. In fact, they have the highest gravimetric energy density from all the solutions that are reversible.
2.5 Electrochemical Batteries:

Working Principles:
Electrochemical batteries are energy storage devices, which are able to convert chemically stored energy into electrical energy during discharging. They are composed of a cathode and an anode, made of two dissimilar metals that are in contact with an electrolyte. When all elements are in contact with each other, a flow of electron is produced. If the process is reversible so that they can be recharged, they are referred to as secondary batteries, in the other case they are primary batteries.

Concerning a solar train, rechargeable batteries will of course be used. Several technologies are available and currently, the lithium-ion (or lithium ion-polymer where the electrolyte is a gel and not a liquid) technology is the best concerning gravimetric energy density, compared to lead-acid, nickel cadmium (NiCd) or nickel-metal-hydride (NiMH).

The nominal voltage of a lithium-ion cell is 3.7V compared to 1.2V for NiCd and NiMH and its capacity, in Ah depends on its size.

2.6 Energy Density and Efficiency:

A professional lithium-ion battery charger allows measuring the energy stored and retrieved from the battery during the charging and discharging process very precisely, as shown in figures 2.12 and 2.13. These measured energies should be preferred for estimating available energy, because the values are always slightly different from the product of the capacity and the nominal voltage. The ratio between them allows computing the efficiency of a charge cycle that is between 95% and 99 %, and knowing the cell weight, we can also compute the gravimetric energy density. The ideal operating temperature varies between the manufacturers but is in general between 0°C and 50°C, the discharge being a little bit more tolerant than the charge. Outside this range, the characteristics of the battery,
especially the capacity and maximal discharge current, decrease. At low temperature for example, the gravimetric energy density drops very rapidly.

Over the 14 years, the energy density increased by 6.6%/year while the price was reduced by 17 %/year. In 2008, the best energy density for commercially available lithium-ion cells is 240Wh/kg which confirms the trend. This strong improvement and cost reduction in battery technology has been driven by the growing market of portable computers and mobile devices (phones, mp3 players, etc.). This progression will certainly continue in the next years leading to more efficient, lighter and cheaper battery technologies.
3.1 Introduction:

Sudan has 4,725 kilometers of narrow-gauge, single-track railroads that serve the northern and central portions of the country. The main line runs from Wadi Halfa on the Egyptian border to Khartoum and southwest to Al Ubayyid via Sannar and Kosti, with extensions to Nyala in Southern Darfur and Wau in Western Bahr al Ghazal, South Sudan. Other lines connect Atbarah and Sannar with Port Sudan, and Sannar with Ad Damazin. A 1,400-kilometer line serves the al Gezira cotton-growing region. A modest effort to upgrade rail transport is currently underway to reverse decades of neglect and declining efficiency. Service on some lines may be interrupted during the rainy season. [18]

Figure 3.1 Sudan railways lines[19]
Table (3.1) Rail construction timeline :-

<table>
<thead>
<tr>
<th>Route</th>
<th>Years</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wadi Halfa- Abu Hamad</td>
<td>1897–1898</td>
<td>350 km</td>
</tr>
<tr>
<td>Abu Hamad – Atbara</td>
<td>1898</td>
<td>244 km</td>
</tr>
<tr>
<td>Atbara – Khartoum</td>
<td>1898–1900</td>
<td>313 km</td>
</tr>
<tr>
<td>Atbara – Port Sudan</td>
<td>1904–1906</td>
<td>474 km</td>
</tr>
<tr>
<td>Station No. 10 – Karima</td>
<td>1905</td>
<td>222 km</td>
</tr>
<tr>
<td>Khartoum - Kosti – El Obeid</td>
<td>1909–1911</td>
<td>689 km</td>
</tr>
<tr>
<td>Hayya - Kassala</td>
<td>1923–1924</td>
<td>347 km</td>
</tr>
<tr>
<td>Kassala - Gedarif</td>
<td>1924–1928</td>
<td>218 km</td>
</tr>
<tr>
<td>Gedarif – Sennar</td>
<td>1928–1929</td>
<td>237 km</td>
</tr>
<tr>
<td>Sennar - Damazin</td>
<td>1953–1954</td>
<td>227 km</td>
</tr>
<tr>
<td>Aradeiba Junction – Babanousa</td>
<td>1956–1957</td>
<td>354 km</td>
</tr>
<tr>
<td>Babanousa – Nyala</td>
<td>1957–1959</td>
<td>335 km</td>
</tr>
<tr>
<td>Babanousa – Wau</td>
<td>1959–1962</td>
<td>444 km</td>
</tr>
<tr>
<td>Girba - Digiam</td>
<td>1962</td>
<td>70 km</td>
</tr>
<tr>
<td>Muglad - Abu Gabra</td>
<td>1995</td>
<td>52 km</td>
</tr>
</tbody>
</table>

Today, after decades of mismanagement and neglect, most of the country's rail track is out of service.

Diesel traction in Sudan:

![Image](image.png)

Figure 3.2 Diesel locomotives at Kosti, Sudan in 2008 [19]

Conversion of Sudan Railways to diesel traction started in the late 1950s, but a few mainline steam locomotives continued in use in
1990, serving lines having lighter weight rails. Through the 1960s, rail essentially had a monopoly on transportation of export and import trade, and operations were profitable. In the early 1970s, losses were experienced, and, although the addition of new diesel equipment in 1976 was followed by a return to profitability, another downturn had occurred by the end of the decade. The losses were attributed in part to inflationary factors, the lack of spare parts, and the continuation of certain lines characterized by only light traffic, but retained for economic development needs and for social reasons.[19]

### 3.2 Sudan Railways Corporation:

SRC operates one of the longest railways in Africa. It operates a 5898 km long single line of 1.067 mm gauge. Sudan Railways Corporation, operating by the Sudan government, provides services to most of the country’s production and consumption centers.

- locomotives and rolling stock Directorate is one of the largest Directorate of S.R.C it’s responsible for the maintenance of S.R.C fleet which is composed of Locomotives, wagons and machinery. The corporation was started by steam locomotives, English diesel electric locomotives and now uses new type locomotives which use new computer technology (Chinese locomotives).

- It has a number of diesel electric locomotives that consist of different models and there are also Hydraulic locomotives for shunting, The following are some general specifications: The maximum axle load in heavy line is 16.5 tons, light line is 13.5 tons and maximum curve in main line is 4° 30‗ (388m),in sub lines are 12° 48‗ (137m)and track gauge is 1067 mm.[20]

- Also have a number of passenger wagons and goods wagons of various kinds, purpose and use, with a tonnage of different (30-35-40-45-50) ton, with stabilized bogies & conventional bogies and there is a program to change all conventional to stabilized ones.
3.2.1 The workshops:

• There are a number of workshops scattered around the country equipped with the potential for light maintenance of locomotives. The maintenance of gross and heavy works have provided them with potential in the city of Atbara workshops.

• Construction of a modern workshop for the maintenance of wagons in Port-Sudan. Workshops conducted by a major maintenance in Khartoum, Port-Sudan and Atbara.

Workshops conducted by a light maintenance deployed in all regions of the country.

• In the main workshops there are lathes workshop, foundry works and welding workshop as well as other assistance and workshops with all these different types of machines to meet the need of main works.

• The following is a Profile of the main sections of the Directorate and its functions

![Figure 3.3 main workshop](image)

A) Main workshops department:

• Do all the maintenance of heavy, light and shunting Locomotives, wagons, equipment and cranes as well as maintenance of all equipment such as lathes. Spread all over regions. This section
includes several workshops in equipment maintenance, operations, welding, lathes, balances and supply regions with tools for rehabilitation.

**B) Manufacturing Department:**

- Manufacture some spare parts for wagons and Locomotives and the rail as foundry and other metal heat treatment and it’s equipped with additional equipment that helps manufacture spare parts and sometimes supply the public tender for the manufacture of special agricultural equipment.

**C) Electricity Department:**

- responsible for electrical installations for all equipment, machinery, cranes, houses offices and maintenance and follow-up of several units including the Directorate of rolling and cooling, air conditioning and maintenance of Locomotives diesel engines and do the routine maintenance of electrical equipment for all existing homes and offices, railway workshops maintenance of generators, imaging and printing machines. Cater for the wiring works to the new extensions in regions.

![Figure 3.4 lathe machine [20]](image)

**3.2.2 Coordinating Service Department:**

- This Department is the focal point in the follow-up performance Locomotives, wagons and the implementation of employment policy by organizing a Locomotives and analysis of failures and the failures
and accidents as well as to analyze the rates of consumption of oil, gasoline and follow-up reports Locomotives performance and then programming involved with the maintenance and traffic management control of the Central Section in the follow-up and operation of main line Locomotives and seminars And stand on the conditions on the trains and Locomotives clock

- Running sheds is responsible for different the work of regions, supply them with spare parts, oil and lubricants of different kinds of Locomotives and wagons.

- It’s control the five regions running shed as follow: 1-Atbara 2-Port-Sudan 3-Khartoum 4-Kosti 5-Babnosa.

3.2.3 Technical affairs and projects department:

- Prepare the technical studies of all offers for Locomotives, wagons and equipment. do the preparation of technical specifications for all the needs of railways and the preparation of the budget for tugs and make the analysis of oils and material and requested spare parts and control stocks and preparation of statistical data and periodic reports.

- Engineers and technicians in this department efforts in research and study, testing and analysis for the improvement and development of systems engineering and work procedures by conducting the necessary adjustments and develop specifications.

3.3 Mechanical workshop:

- Full supervision on the property of small and light cars and mobile cranes, lifters and technical assistance in overhauling machines small diesel and gasoline engines.
3.4 Commercial production:

- This section runs the business of the maintenance workshops, manufacturing and electricity to provide business services to workers and the public institutions, including the work of wood and iron furniture and the needs of special workshop equipment and spare parts and Castings.

3.5 ATBARA, ALKHARTOUM passenger train (DMU):

A new passenger train introduced at Atbara al Khartoum line, it set is specially designed as per the requirements from Sudan railways. Its maximum running speed is 100km/h, which can fully meet passenger transportation demands for Sudan railways.

DMU is consist of two leading locomotives and four trailing coaches. First and last one are the leading locomotives and the others are trailing coaches, the capacity of seating coaches ≥ 66 persons[21].

Figure 3.5 ATBARA, ALKHARTOUM passenger train[21]
4.1 Introduction:

The primary function of an air conditioning system is to maintain the conditioned space at required temperature, moisture content with due attention towards the air motion, air quality and noise. The required conditions are decided by the end use of the conditioned space, e.g. for providing thermal comfort to the occupants as in comfort air conditioning applications, for providing suitable conditions for a process or for manufacturing a product as in industrial air conditioning applications etc.

The reason behind carrying out cooling and heating load calculations is to ensure that the cooling and heating equipment designed or selected serves the intended purpose of maintaining the required conditions in the conditioned space.

Design and/or selection of cooling and heating systems involve decisions regarding the required capacity of the equipment selected, type of the equipment etc. By carrying out cooling and heating load calculations one can estimate the capacity that will be required for various air conditioning equipment.

For carrying out load calculations it is essential to have knowledge of various energy transfers that take place across the conditioned space, which will influence the required capacity of the air conditioning equipment. Cooling and heating load calculations involve a systematic step-wise procedure by following which one can estimate the various individual energy flows and finally the total energy flow across an air conditioned building.
To estimate the required cooling or heating capacities, one has to have information regarding the design indoor and outdoor conditions, specifications of the building, specifications of the conditioned space (such as the occupancy, activity level, various appliances and equipment used etc.) and any special requirements of the particular application.[22]

**4.2 Air conditioning load estimation :-**

**4.2.1. Estimation of external loads:**

**a) Transmission load :**
This is a sensible heat transfer process. The heat transfer rate through opaque surfaces such as walls, roof, floor, doors etc. is given by:

\[
Q_{\text{opaque}} = U \cdot A \cdot CLTD \tag{4.1}
\]

where \(U\) is the overall heat transfer coefficient and \(A\) is the heat transfer area of the surface on the side of the conditioned space. \(CLTD\) is the cooling load temperature difference.

**b) Heat transfer through fenestration:**
Heat transfer through transparent surface such as a window, includes heat transfer by conduction due to temperature difference across the window and heat transfer due to solar radiation through the window. The heat transfer through the window by convection is calculated using Eq.(4.1), with

\[
CLTD = \text{temperature difference across the window}
\]

\[
A = \text{total area of the window}
\]

The heat transfer due to solar radiation through the window is given by:

\[
Q_{\text{trans}} = A_{\text{un shaded}} \cdot \text{SHGF max} \cdot \text{SC} \cdot \text{CLF} \tag{4.2}
\]

where \(A_{\text{un shaded}}\) is the area exposed to solar radiation, SHGF max and SC are the maximum Solar Heat Gain Factor and Shading Coefficient, respectively, and \(\text{CLF}\) is the Cooling Load Factor.
c) **Heat transfer due to infiltration and ventilation:**

Heat transfer due to infiltration and ventilation consists of both sensible and latent heat.

The sensible heat transfer rate due to ventilation and infiltration, $Q_{s,v}$, is given by:

$$Q_{s,v} = 0.35 \times n \times q \times (T_o - T_i) \quad (4.3)$$

The latent heat transfer rate due to ventilation and infiltration, $Q_{l,v}$, is given by:

$$Q_{l,v} = 0.87 \times n \times q \times (\omega_o - \omega_i) \quad (4.4)$$

Where $n$ is number of people, $q$ litter/hour for one person, $T_o$ and $T_i$ are the outdoor and indoor dry bulb temperatures and $\omega_o$ and $\omega_i$ are the outdoor and indoor humidity ratios. Thus from known indoor and outdoor conditions and computed or selected values of ventilation and infiltration rates, one can calculate the cooling and heating loads on the building. The sensible and latent heat transfer rates as given by the equations above will be positive during summer (heat gains) and negative during winter (heat losses) [23].

### 4.2.2. Estimation of internal loads:

The internal loads consist of load due to occupants, due to lighting, due to equipment and appliances and due to products stored or processes being performed in the conditioned space.

**a) Load due to occupants:**

The internal cooling load due to occupants consists of both sensible and latent heat components.

Thus the sensible heat transfer to the conditioned space due to the occupants is given by the equation:

$$Q_{s, \text{ occupants}} = (\text{No. of people}) \times (\text{Sensible heat gain / person}) \times \text{CLF} \quad (4.5)$$
Since the latent heat gain from the occupants is instantaneous the CLF for latent heat gain is 1.0, thus the latent heat gain due to occupants is given by:

\[ Qi, \text{ occupants} = (\text{No. of people}).(\text{Latent heat gain/person}). \] (4.6)

b) Load due to lighting:
Lighting adds sensible heat to the conditioned space. Since the heat transferred from the lighting system consists of both radiation and convection, a Cooling Load Factor is used to account for the time lag. Thus the cooling load due to lighting system is given by:

\[ Qs, \text{ lighting} = (\text{Installed wattage})(\text{Usage Factor})(\text{Ballast factor})\text{CLF}. \] (4.7)

c) Internal loads due to equipment and appliances:
The equipment and appliances used in the conditioned space may add both sensible as well as latent loads to the conditioned space. Again, the sensible load may be in the form of radiation and/or convection.[26]
Thus the internal sensible load due to equipment and appliances is given by:

\[ Qs, \text{ appliances} = (\text{Installed wattage})(\text{Usage Factor}).\text{CLF}. \] (4.8)

The latent load due to appliances is given by:

\[ Qi, \text{ appliance} = (\text{Installed wattage})(\text{Latent heat fraction}) \] (4.9)
4.3 Air conditioning calculation for a train coach:

4.3.1 External load:

a) Walls calculation:

For (W and E) walls
\[ Q = A \times U \times (T_i - T_o) \]

Wall material: we need to know the different types of material which used in coach body and it is shown in a table below (21).

**Table (4.1) coach wall material :-**

<table>
<thead>
<tr>
<th>NO</th>
<th>Martial</th>
<th>Thickness</th>
<th>K(w/m k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(Anti-climate nickel-chrome steel+05cupcrNi+09cupcrNI-B+ Steel plate)coach body</td>
<td>20mm</td>
<td>1.16</td>
</tr>
<tr>
<td>2</td>
<td>Fiber glass</td>
<td>6mm</td>
<td>0.038</td>
</tr>
<tr>
<td>3</td>
<td>Plywood</td>
<td>3mm</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>Aluminum foil</td>
<td>6mm</td>
<td>235 W/m.K [24]</td>
</tr>
<tr>
<td>5</td>
<td>Plastic</td>
<td>4mm</td>
<td>0.03</td>
</tr>
<tr>
<td>6</td>
<td>(Plastic + plywood) will be used to furnish interior wall and roof plates</td>
<td>6mm</td>
<td>(0.03 , 0.12)</td>
</tr>
<tr>
<td>7</td>
<td>PVC</td>
<td>3mm</td>
<td>0.19</td>
</tr>
</tbody>
</table>

to find U we must calculate the inner and outer convection coefficients.

\[ \frac{1}{U} = \left[ \frac{1}{H_o} + \sum \frac{X_n}{K_n} + \frac{1}{H_i} \right] \]  \hspace{1cm} (4.10)
Heat transfer coefficient :-

To calculate the inner and outside heat transfer coefficient we must know the Reynoulds (Re) number and Prandtl (Pr) number.

Heat transfer coefficient at outside temperature 43°C [ho]:
\[ Re = \frac{\rho l v}{\mu} \]
Where:
Re : Reynoulds number, \( \rho \) : air density (kg /m\(^3\)), L : length(m), V : velocity (m/s), \( \mu \) : dynamic viscosity (kg/m s).

\[ Re = \frac{1.11876 \times 80 \times 1000 \times 22}{3600 \times 1.92024 \times 10^{-5}} \]
Re = 284.834 \times 10^5 (so the flow is turbulent)

Pr = 0.70316 at 43°C (from tables)

\[ Nu = 0.0308(Re)^{4/5}(Pr)^{1/3} \]
\[ Nu = 0.0308(284.834 \times 10^5)^{4/5}(0.70316)^{1/3} \]
\[ Nu = 25190.8158 \]

\[ Nu = \frac{h_0 l}{k} \]
Where : Nu : nustel number, Ho : outside heat transfer coefficient (w/m\(^2\)K), L : length(m), k : the ratio of specific heat

25190.8158 = (h\times22)/0.0274688
The outside heat transfer coefficient is found as \( h_0 = 31.453 \) (w/m\(^2\)K)

Heat transfer coefficient at inside temperature 25°C [hi]:
\[ Re = \frac{\rho l v}{\mu} \]
\[ Re = \frac{1.18556 \times 22 \times 5}{1.83632 \times 10^{-5}} \]
Re = 71.018 \times 10^5

Pr = 0.7075 (from tables)

\[ Nu = 0.0308(Re)^{4/5}(Pr)^{1/3} \]
\[ Nu = 0.0308(71.018 \times 10^5)^{4/5}(0.7075)^{1/3} \]
Nu = 0.0308(71.018*10^5)^(4/5)*(0.7075)^(1/3)
Nu = 8309.1056
Nu = (hi*l)/k
8309.1056 = (hi*22)/0.0260832
The inside heat transfer coefficient is found as hi= 9.8513(w/m²K)

a) For (W and E) walls

Q = A*U*(Ti-To)
1/U=[1/Ho+∑Xn/Kn+1/Hi]

1/U = [1/31.453 +0.2/1.16+0.006/0.038+0.003/0.12+0.006/235+0.004/0.03+0.003/0.03+0.003/0.12+1/9.85126] = 0.747
U = 1.33874
A for walls = total area – glass windows area (9 windows)
A = (22*3)-(1.15*.85*9)
A = 57.2025 m²
Q= A*U*(To –Ti)= 57.2025*1.33874*(43 -25 ) = 1.3784 kW

b) Glass calculation :
For E side :-
Qe = A*SHG*CLF*SC
A = (1.15* 0.85*9 (number of window)) =8.7975m²
Qe = 8.7975*700*0.6*0.76 = 2.808 kW
For W side :-
Qw = 8.7975 * 700*0.6 *0.13 = 0.48034 kW

c) Roof calculation :

Qr = A*U*(To –Ti)
A = 22 * 2.804 = 61.688m²
Qr = 61.688 * 1.33874 * (43 -25 ) =1.4865 kW
d) Floor calculation:

\[ Q_f = A \cdot U \cdot (T_0 - T_i) \]

\[ \frac{1}{u} = \frac{1}{31.453} + \frac{0.2}{1.16} + \frac{0.003}{0.19} + \frac{1}{9.85126} = 0.3215067 \]

\[ U = 3.110356 \]

\[ A = 22 \times 2.804 = 61.688 \text{ m}^2 \]

\[ Q_f = 61.688 \times 3.110354 \times (35 - 25) = 1.9187 \text{ kW} \]

e) Ventilation load calculation:

The sensible heat transfer rate due to ventilation and infiltration, \( Q_{s, vi} \), is given by:

\[ Q_{s, vi} = 0.35 \times n \times q \times (T_0 - T_i) \]  \hspace{1cm} (4.11)

\( N \) = number of people

\( Q \) = litter/hour for one person

\[ Q_{s, vi} = 0.35 \times 70 \times 9 \times (43 - 25) = 3.969 \text{ kW} \]

The latent heat transfer rate due to ventilation and infiltration, \( Q_{l, vi} \), is given by:

\[ Q_{l, vi} = 0.87 \times n \times q \times (w_0 - w_i) \]  \hspace{1cm} (4.12)

Outside humidity ratio:
At 43°C \( w_0 = 0.0195 \), relative humidity 30% from psychometric chart

Inside humidity ratio:
At 25°C \( w_i = 0.008 \), inside relative humidity = 40% from psychometric chart

\[ Q_i = 0.87 \times n \times q \times (w_0 - w_i) \]

\[ Q_i = 0.87 \times 70 \times 9 \times (0.0195 - 0.008) = 6.303 \text{ kW} \]

\[ Q \text{ total} = 6.303 + 3.969 = 10.272 \text{ kW} \]
4.3.2 Internal loads:

a) occupants calculation:
Q occupants = no of people * total heat gain
Total heat gain = latent heat + sensible heat
Q occupants = 150*70 = 10.5 kW

b) Lighting load:

= Installed watts * clf * Ballast factor
= 1.93*1*1.25 = 2.4125 kW
Total load = (1.3784 * 2) + 2.808 + 0.48034 + 10.5 + 1.4865 + 1.9187 + 2.4125 + 10.272 = 32.635 kW = 9.2977 TR
CHAPTER [5]

PV SYSTEM SELECTION

5.1 Introduction:

It was difficult to find many papers that have looked into the interaction between air conditioners and photovoltaic electricity. Most research conducted had been in other areas such as solar cooling, like absorption and adsorption.

This chapter presents the possibility of using photovoltaic panels to produce electricity that is used to power the AC air conditioning unit and DC air conditioning unit and then choose the suitable one for this application.

5.2 AC air conditioning unit powered by PV system:

With a large solar potential it could be possible to design an off grid system with no batteries. Solar panels would connect to an inverter and then to an AC air conditioner. This would be a simple system. With so few components it would be easily installed and maintained. With no battery or grid back up this system would be completely dependent on the weather.

To meet the startup power needed the panels would have to be greatly oversized which would become very costly canceling out the benefit of not having batteries. Additionally, the inverter would have to be oversized to meet the air conditioner start-up power which would lower the running efficiency of the inverter.

5.2.1 Major PV system components:

Solar PV system includes different components that should be selected according to your system type, site location and applications.
The major components for solar PV system are solar charge controller, inverter, battery bank, auxiliary energy sources and loads (appliances).

At this system components will be:

- **PV module** – converts sunlight into DC electricity.
- **Solar charge controller** – regulates the voltage and current coming from the PV panels going to battery and prevents battery overcharging and prolongs the battery life.
- **Inverter** – converts DC output of PV panels or wind turbine into a clean AC current for AC appliances or fed back into grid line.
- **Battery** – stores energy for supplying to electrical appliances when there is a demand.
- **Load** – is electrical appliances that connected to solar PV system such as lights, air conditioning, radio, TV, computer, refrigerator, etc.

**5.2.2 Solar PV system sizing:**

**Determine power consumption demands**

The first step in designing a solar PV system is to find out the total power and energy consumption of all loads that need to be supplied by the solar PV system as follows:

a) **Calculate total Watt-hours per day for each appliance used.**

   Add the Watt-hours needed for all appliances together to get the total Watt-hours per day which must be delivered to the appliances.
Total load = cooling load / cop for the compressor

Cooling load = 9.2977*3.51 = 32.635 kW

Total load = 32.635 kW / 2.81 = 11.6 kW

b) **Calculate total Watt-hours per day needed from the PV modules.**

Multiply the total appliances Watt-hours per day times 1.3 (the energy lost in the system) to get the total Watt-hours per day which must be provided by the panels.

Required energy = 11.6 kW
Operation hours during a day = 10 hours from 7am to 4pm for lighting and cooling loads.

Required energy in 10 hours = 116 kWh
Total watts = 116 * 1.3 = 150.8 kwh = 150800 Wh

5.2.3 **Size the PV modules:**

Different size of PV modules will produce different amount of power. To find out the sizing of PV module, the total peak watt produced needs. The peak watt (Wp) produced depends on size of the PV module and climate of site location. We have to consider “panel generation factor” which is different in each site location. To determine the sizing of PV modules, calculate as follows:

Numbers of no-sun days = 0

Expected ambient temperature:

Annual extreme low temperature: 15 °C
Average high Temperature: 40 °C
Annual extreme high temperature: 45 °C
Location: Khartoum, Sudan

Table (5.1) global radiation and sunshine duration [26]:

<table>
<thead>
<tr>
<th>Station</th>
<th>E</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
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<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Average</th>
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<tbody>
<tr>
<td>أبوتمني</td>
<td>G</td>
<td>5.0</td>
<td>6.9</td>
<td>7.4</td>
<td>7.2</td>
<td>7.2</td>
<td>6.6</td>
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<td>6.3</td>
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<td>%</td>
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<td>6.8</td>
<td>5.9</td>
<td>6.2</td>
<td>7.0</td>
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<td>D</td>
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<td>9.2</td>
<td>10.2</td>
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</tr>
<tr>
<td>%</td>
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<td>8.7</td>
<td>7.9</td>
<td>7.8</td>
<td>7.3</td>
<td>6.6</td>
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<td>5.6</td>
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</tr>
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<td>G</td>
<td>5.9</td>
<td>6.3</td>
<td>6.4</td>
<td>6.7</td>
<td>5.9</td>
<td>4.8</td>
<td>5.6</td>
<td>5.0</td>
<td>5.1</td>
<td>5.6</td>
<td>6.0</td>
<td>6.3</td>
<td>5.8</td>
</tr>
<tr>
<td>D</td>
<td>9.9</td>
<td>9.9</td>
<td>8.9</td>
<td>9.3</td>
<td>8.6</td>
<td>5.6</td>
<td>5.9</td>
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<td>8.1</td>
<td>10.1</td>
<td>10.1</td>
<td></td>
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<tr>
<td>%</td>
<td>8.6</td>
<td>8.4</td>
<td>7.3</td>
<td>7.5</td>
<td>6.7</td>
<td>4.3</td>
<td>4.6</td>
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</tr>
<tr>
<td>سدير النصر</td>
<td>G</td>
<td>5.3</td>
<td>5.8</td>
<td>6.1</td>
<td>6.1</td>
<td>5.4</td>
<td>7.2</td>
<td>4.5</td>
<td>4.9</td>
<td>5.1</td>
<td>5.2</td>
<td>5.4</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>D</td>
<td>9.5</td>
<td>9.4</td>
<td>8.4</td>
<td>8.7</td>
<td>7.4</td>
<td>9.5</td>
<td>4.9</td>
<td>5.5</td>
<td>5.9</td>
<td>7.2</td>
<td>9.4</td>
<td>9.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>%</td>
<td>8.2</td>
<td>8.0</td>
<td>7.0</td>
<td>7.0</td>
<td>5.8</td>
<td>4.3</td>
<td>3.9</td>
<td>4.3</td>
<td>4.8</td>
<td>6.1</td>
<td>8.1</td>
<td>8.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: G= Global radiation in kw/m²2/day
D= Bright sun shine duration

Table 5.1 above show the average solar irradiance in Khartoum = 6.2kWh/m²
Mounting type: roof type
Available module: ET-P660255WW (255W)
The system voltage = 220 V
System current = 150800/220 = 685.5 Ah
No of module required = 685.5/(I_{mp} * (monthly mean global solar radiation on a horizontal surface in Khartoum))
No of module required = \( \frac{685.5}{(8.42 \times 6.34)} = 12.84 \)
≈ 13 modules in parallel.

No of modules in series = \( \frac{220}{V_{mp}} = 220 / 30.29 = 7.26 \)
≈ 8 modules in series.

Total no of modules = 8 * 13 = 104 modules

Total power produced from these modules = 26,520 W

5.2.4 solar charge controller:

\( C.C = \text{No of modules in parallel} \times \text{module current} \times 1.3 \)

\( C.C = 13 \times 8.42 \times 1.3 = 142.3A \)
≈ 150A, 220V

5.2.5 Inverter sizing

Off grid inverters, can also be a solar inverter, have no back up from the grid and must be able to power all planned appliances by itself. The rated power of the inverter must be at least the operating power of the planned load. Inverters can also release a much higher power for a short time, which can be twice as high. Sometimes manufacturers state for how long the inverter can release power for different output powers higher than the rated power. The peak power of an inverter is stated by manufacturers in watts. But this power can only be supplied to resistive loads with a power factor \( \cos \phi = 1 \). If the power factor much lower, like for compressors in air conditioners, it is much better to look for the surge current of the inverter. the current is crucial factor which puts a strain on the inverter. The start-up power (apparent power, not true power) is typically 3 to 8 times higher than the operating power for air conditioners and with it the current. This needs to be considered when sizing an inverter.

Total required power = 15.08 kW

Inverter sizing = 15.08 * 3 = 45.24 kW

Inverter sizing ≈ 50kW (JIANGSU EKSI Electrical MANUFACTURING CO., LTD 50kW off grid inverter) [25]
5.2.6 Battery sizing:

- we will use batteries with storage (150Ah, 12V)
- Cycle life to 80% depth of discharge (DOD).
- Charge efficiency from 20% discharged.

Energy required from batteries = \( \frac{685.5}{DOD} = \frac{685.5}{0.8} = 856.88 \text{Ah} \)

Storage battery capacity = \( \frac{856.88}{150} = 5.71 \approx 6 \text{ batteries in parallel} \)

No of batteries in series = \( \frac{220}{12} = 18.3 \approx 19 \)

Total no of batteries = 19*6 = 114

5.2.7 Cables selection:
Voltage drop in photovoltaic systems (220 V) \( \leq 5\% = 11V \)

\[ V_{\text{drop}} = I*R = I*(\rho*L)/a \]

Where:
- \( I \): system current
- \( \rho \): resistivity of copper wire = \( 40*10^{-8} \Omega.m \)
- \( L \): length
- \( A \): cross sectional area

\[ 11 = 150 * (40*10^{-8}*10)/A \]

\[ A = 0.54545 * 10^{-4} \text{ m}^2 = 54.545 \text{mm} \]

Advantages
- Very simple system
- Easy to connect
- Reliable

Disadvantages
- PV modules have to be extremely oversized
- System need large area for installation so additional coach will be added.
- the inverter would have to be oversized
- the cost is very high
5.3 DC solar powered air conditioner unit:

DC solar air conditioning system is designed for off-grid applications. The unit itself runs off DC power, and photovoltaic modules produce DC power. Therefore, all components in the DC air conditioning systems such as compressors, fan motors, solenoids, valves etc. are powered by direct current so if this option is applied on train coach the Conventional AC air conditioning unit will be replaced. Because solar panels produce direct current (DC) it can be fed directly to the air conditioner. This eliminates the use of an inverter, which can reduce cost and increase efficiency. A lot of types of 100% DC air conditioner in different capacities available in world market.

5.4 Economical analysis :-

The Conventional system:
work on AC current powered by a diesel generator which is power also lighting ,control equipment ,others. coach total consummation is 40 kw and it is selected to meet the demand of two coach , air conditioning consume 66.67% of power output from the generator . this generator is full damaged during one year because it was not suitable for our operation conditions and replaced by new one. Initial cost :35500 $US
Table (5.2) below explains the running cost for one month (diesel generator):

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Price SDG</th>
<th>Total amount SDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor</td>
<td>2</td>
<td>1500</td>
<td>3000</td>
</tr>
<tr>
<td>Oil filter</td>
<td>2</td>
<td>240</td>
<td>480</td>
</tr>
<tr>
<td>Jas filter</td>
<td>2</td>
<td>450</td>
<td>900</td>
</tr>
<tr>
<td>Air filter</td>
<td>2</td>
<td>631.79</td>
<td>1263.58</td>
</tr>
<tr>
<td>Engine oil</td>
<td>1</td>
<td>5720.14</td>
<td>5720.14</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>1</td>
<td>68112</td>
<td>68112</td>
</tr>
<tr>
<td>Total cost</td>
<td></td>
<td></td>
<td>79475.72 SDG</td>
</tr>
</tbody>
</table>

One Primary maintenance during a year will cost = 21363.72 SDG

As can be seen from table 5.2 above the running cost for one year
= (79475.72 * 11) + 21363.72 + 68112 =
963708.64 SDG = 63,971.2 USD

To find the perfect option to power air conditioning unit the Net Present Worth should be found. If the expected life time for this systems is 25years.

\[ Net \text{ Present Worth of Project (NPW)} = Total \text{ Benefit} - Total \text{ cost} \]

Total benefit term will be ignored because it is equal in all options so only the cost term will be calculated

\[ Total \text{ Benefit} = \text{Presnt value of Annual benefit} = A \left( \frac{(1 + i)^n - 1}{i(1 + i)^n} \right) \]
Total Cost = Present Value of Future cost = \( F(1 + i)^{-n} \)

Where:
A: Annual benefit (SDG)
F: Future cost (SDG)
i: Interest rate (0.4 )
n: Number of year (year)

\[
0 \qquad 1 \quad 2 \quad 3 \quad 4 \quad 25
\]

\[
35500\$
\]

\[
63971\$
\]

\[
FV = F = A \frac{(F/A, i, n)}{1+i}
\]

\[
F = 63971 \frac{(F/A, 0.4, 25)}{1+0.4} = 63971 \times 11274 = 721,209,054\$
\]

Total cost = present value of future cost = \( F(1+i)^{-n} \)

\[
= 721,209,054(1+0.4)^{-25} = 160,273\$
\]

Total cost = -(35,500+160,273) = 195,773$

Because air conditioning unit consume 66.67% of power so the cost will be = -195,773 *0.6667 = 130,522$
Table (5.3) The initial cost for Ac air conditioning unit powered by PV system for one coach:

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
<th>Unit price</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV modules, Poly-crystalline</td>
<td>104</td>
<td>142.8 $</td>
<td>14,851.2 $</td>
</tr>
<tr>
<td>Charge controller</td>
<td>1</td>
<td>800 $</td>
<td>800 $</td>
</tr>
<tr>
<td>Schletter ClampFit-H mounting instructing</td>
<td>219</td>
<td>4.7$</td>
<td>1,029.3</td>
</tr>
<tr>
<td>Batteries</td>
<td>114</td>
<td>205.36 $</td>
<td>23,114 $</td>
</tr>
<tr>
<td>Cables</td>
<td>10 m</td>
<td>71.428 $</td>
<td>714.28 $</td>
</tr>
<tr>
<td>Inverters</td>
<td>1</td>
<td>5100 $</td>
<td>9,600 $</td>
</tr>
<tr>
<td>Others</td>
<td>-</td>
<td>-</td>
<td>500 $</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>50,608.78$</strong></td>
</tr>
</tbody>
</table>

As shown in table 5.3 the total cost For two coach = 101,217.56$

**And the running cost** = 0 USD and batteries will be replaced every five years (for two coach = 23,114 $ \times 2 = 46228$).

\[
Net\ Person Worth\ of\ Project (NPW) = Total\ Benefit - Total\ cost
\]

Total Benefit = Present value of Annual benefit = \(A \left(\frac{(1 + i)^n - 1}{i(1 + i)^n}\right)\)

Total Cost = Present Value of Future cost = \(F(1 + i)^{-n}\)

Where:
A: Annual benefit (SDG)
F: Future cost (SDG)
i: Interest rate (0.4)
n: Number of year (year)
Present value of future cost = $46,228(1+0.4)^{-5} + 46,228(1+0.4)^{-10} + 46,228(1+0.4)^{-15} + 46,228(1+0.4)^{-20} = 8,595.4 + 1,598.2 + 297.2 + 22.52 = 10,513.32$

Total cost = (101,217.56 + 10,513.32) = 111,730.88$

By comparing the total cost of two systems above we found AC air conditioning unit powered by PV system is the best option economically.

**Table (5.4) DC solar air conditioner units:**

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>Part no</th>
<th>Cooling capacity (BTU)</th>
<th>Application</th>
<th>Voltage</th>
<th>Unit Price $ US</th>
</tr>
</thead>
<tbody>
<tr>
<td>Securus Air</td>
<td>DC4812VRF</td>
<td>12000</td>
<td>Stationary</td>
<td>48V</td>
<td>1795 $</td>
</tr>
<tr>
<td>Kingtec</td>
<td>K25Z-4</td>
<td>16000</td>
<td>Stationary</td>
<td>48V</td>
<td>2895 $</td>
</tr>
<tr>
<td>Ecool</td>
<td>H24K/SWDI</td>
<td>24000</td>
<td>Stationary</td>
<td>48V</td>
<td>3310 $</td>
</tr>
</tbody>
</table>
Table 5.4 above show different types of solar air conditioners suppliers and capacities. 
The coach cooling load = 9.3 kw = 111600 BTU
So we choose Ecool DC air conditioner from table 5.4 ( 5 units ) 24000BTU to meet the cooling demand.
100% solar air conditioner consists of solar PV panels, Solar Charging Controller, DC inverter air conditioner and solar UPS system (including batteries and inverter), which Driven by solar in the daytime & by UPS in the evening. UPS system can be supplie locally, while100% solar air conditioner is equipped with a special solar charging controller, which can charge batteries directly from PV panel array during day time.

![Figure 5.1 ECOOL DC solar air conditioner](image-url)
we will ignore PV array sizing in ECOOL air conditioner and do a new PV array sizing to be more accurate.

**PV system sizing:**

Cooling load = 32.635 kW
Total load = cooling load / COP for the compressor
Total load = 32.635/3.51 = 9.3 kW
Operation hours during a day = 10 hours from 7am to 4pm for lighting and cooling loads.

Required energy in 10 hours = 93kWh
Total watts = 93 * 1.3 = 120.9 kwh = 120,900 Wh

**PV modules sizing:**

Available module : ET-P660255WW (255W)
Mounting type : roof type
The system voltage = 220 V
System current = 120,900/220 = 549.54 Ah
No of module required = $\frac{549.54}{(I_{mp} \times (\text{monthly mean global solar radiation on a horizontal surface in Khartoum})^{38})}$

No of module required = $\frac{549.54}{(8.42 \times 6.34)} = 10.29$

$\approx 11$ modules in parallel.

No of modules in series = $\frac{220}{V_{mp}} = \frac{220}{30.29} = 7.26$

$\approx 8$ modules in series.

Total no of modules = $8 \times 11 = 88$ modules

Total power produced from these modules = 22,440 W

**Solar charge controller:**

C.C = No of modules in parallel * module current ($I_{mp}$) * 1.3

C.C = $11 \times 8.42 \times 1.3 = 120.406$ A

$\approx 150$ A, 220V

**Battery sizing:**

- we will use batteries with storage (150Ah, 12V)
- Cycle life to 80% depth of discharge (DOD).
- Charge efficiency from 20% discharged.

Energy required from batteries = $\frac{549.54}{DOD} = \frac{549.54}{0.8} = 686.92$ Ah

Storage battery capacity = $\frac{686.92}{150} = 5.71 \approx 5$ batteries in parallel

No of batteries in series = $\frac{220}{12} = 18.3 \approx 19$

Total no of batteries = $19 \times 5 = 95$

**Cables selection:**

Voltage drop in photovoltaic systems (220 V) $\leq 5\% = 11$ V

$V_{drop} = I \times R = I \times (\rho \times L) / a$

Where:

I : system current
ρ : resistivity of copper wire = $40 \times 10^{-8} \, \Omega.m$
L : length
A : area
\[ 11 = 150 \times (40 \times 10^{-8} \times 10) / A \]
\[ A = 0.54545 \times 10^{-4} \, m^2 = 54.545\text{mm} \]

The Initial cost to utilize DC solar air conditioning units:
Total cost for DC air conditioner option is = $5 \times 3310 = 16550$
For two coach = $33100$

**Table (5.5) Initial cost for the DC solar air conditioning system:**

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
<th>Unit price</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV modules , Poly-crystalline</td>
<td>88</td>
<td>142.8 $</td>
<td>12,566.4 $</td>
</tr>
<tr>
<td>Charge controller</td>
<td>1</td>
<td>800 $</td>
<td>800 $</td>
</tr>
<tr>
<td>Batteries</td>
<td>95</td>
<td>205.36$</td>
<td>19,509.2$</td>
</tr>
<tr>
<td>Cables</td>
<td>10</td>
<td>71.428$</td>
<td>714.28$</td>
</tr>
<tr>
<td>Dc unit</td>
<td>5</td>
<td>3,310$</td>
<td>16,550$</td>
</tr>
<tr>
<td>Total cost</td>
<td></td>
<td></td>
<td>50,139.48$</td>
</tr>
</tbody>
</table>

DC air conditioning units and batteries will be replaced every 5 years.
The running cost for two coach will be = $(33100+2 \times 19,509.2) = 72,118.4$, and the initial cost 100,278.96$

*Net Present Worth of Project (NPW) = Total Benefit − Total cost*

\[
Total \ Benefit = Presnt \ value \ of \ Annual \ benefit = A \left( \frac{(1 + i)^n - 1}{i(1 + i)^n} \right)
\]

\[
Total \ Cost = Present \ Value \ of \ Futur \ cost = F(1 + i)^{-n}
\]

Where:
A: Annual benefit (SDG)
F: Future cost (SDG)
i: Interest rate (0.4)
n: Number of year (year)
Present value of future cost = $F(1+i)^n$

\[
= 72,118.4(1+0.4)^{-5} + 72,118.4(1+0.4)^{-10} + 72,118.4(1+0.4)^{-15} \\
+ 72,118.4(1+0.4)^{-20} = 13,409.3 + 2,493.25 + 463.58 + 86.19 + 16 = 16,468.3$

Total cost = (100,278.96 + 16,468.3) = 116,747.3$

Obviously this option is the best one economically.

**Table (5.6) comparison between the three systems:**

<table>
<thead>
<tr>
<th>Item</th>
<th>Initial cost</th>
<th>running cost</th>
<th>No of modules for one coach</th>
<th>Total area needed (available area = 66 m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional system</td>
<td>35500</td>
<td>63,971.2</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Solar AC powered system</td>
<td>92,217.56</td>
<td>46,228</td>
<td>104</td>
<td>For one module = 1.627 m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>For 104 = 169.2 m²</td>
</tr>
<tr>
<td>Solar DC powered system</td>
<td>66,689.88</td>
<td>52609.2</td>
<td>95</td>
<td>143.176 m²</td>
</tr>
</tbody>
</table>
As shown in table 5.6 the conventional system is the most expensive system and the AC solar air conditioning unit is the cheapest one.

On the other hand conventional system occupy the smallest area than the solar systems, the AC solar air conditioner need a large area for installation.

The DC is resized to meet the power requirement in our environment so the area need for installation is oversized.
6.1 Conclusion:

In this thesis the possibility of using direct solar PV energy to power an air conditioning unit in a train coach during the day was studied, PV system is very simple.

At first cooling load is estimated for the passengers compartment as 32.635 kW (9.3 TR), then a PV system is sized to meet the energy consumption of the AC air conditioning unit.

Suitable PV modules (104 modules) and inverter are chosen. but off grid systems require oversizing of components and need large area for installation (169.2m$^2$) which was difficult to be available in one coach ( available area 60m$^2$).

Using AC air conditioning unit can be a suitable option if two commodity coaches are attached to the passenger coach to use their roof area to achieve the required energy.

Also the option of using DC solar air conditioning unit is discussed in detail all components in the air conditioning system such as compressors, fan motors, solenoids, valves etc., are considered to be powered by direct current.

The amount of energy required to power the DC solar air conditioner is founded less than the AC solar air conditioning system for the
same cooling load (9.3 TR), the PV system used for DC air conditioner is resized to be valid this step make DC system very expensive.

Finally a short economical analysis is done for all considered options and a AC solar air conditioning unit was found to be suitable to be utilized for the job because it is the cheapest option.

As a result we can achieve the desired pleasant and comfortable interior thermal environment for the passengers at all expected external ambient environmental conditions, during the day time.

6.2 Recommendations:

The AC system option is recommended to be applied in Sudan railways as a pilot solar system to encourage future full utilization in all trains.
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