BENCHMARKING ENERGY MANAGEMENT SYSTEMS

IN METRO STATIONS

by

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Dedication

To my mother…

Abstract

Energy and environmental sustainability have become central objectives in mobility system design and mass transit schemes. In addition to environmental prudence, a new world economic order calls for more efficient use of financial resources. This study focuses on developing a benchmarking technique to measure the degree to which energy management systems are utilized in metro stations by reviewing the broad literature in energy management in the transportation and construction sectors and exploring the techniques used to reduce energy consumption. A System Application Matrix is constructed using the Quality Function Development approach and Analytic Hierarchy Process in which the model has three main energy management categories: an energy efficiency system, a renewable energy system and a recovery energy system. Each main category includes a subcategory or subcategories. For example, the LED lighting system, walls insulation and platform screen doors are the subcategories of the energy efficiency system. Solar panel is the only subcategory of the renewable energy efficiency system and energy storage is also the only subcategory of the recovery energy system. The optimal design of these five subcategories will be provided for developing the System Application Matrix. Furthermore, the System Application Matrix is validated via industry and academia experts' input, using the Analytic Hierarchy Process and piloted on theoretical data runs. After prioritizing the experts' judgments, the energy efficiency system had the highest priority (61.2%) compared to the two other main categories of the energy management system. Consequently, after Quality Function Development matrix analysis, LED lighting had the highest level of importance by almost 29.1%. The next highest elements were wall insulation and platform screen doors by almost 26.2%. Solar panels, with 9.8%, and energy storage, with 8.7%, were the last two elements in terms of relative importance. Ultimately, the System Application Matrix, which is a "Best in Class" benchmarking model, is considered to be an integration model providing both government and private sectors with the ability to measure the level of importance of applied energy management elements in metro stations.

Search Terms: Energy Management Systems in Metro Stations, System Application Matrix, Analytic Hierarchy Process, Quality Function Development, Energy Management Benchmarking Tools, "Best in Class" Metro Station.

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Chapter 1: Introduction

1.1 Background

Recently, a report by the Intergovernmental Panel on Climate Change stated that the amount of global greenhouse gas emissions (GHG) must be reduced by almost 60% by 2050 [1]. However, developed countries would have difficulty in combining strong emission reduction with fast economic growth. Because of the high dependency of transport systems on oil-derived fuels and internal combustion engines, reducing the amount of Green House Gases (GHG) emitted by transport systems by up to 60% seems impossible [1]. Furthermore, the rapid increase in oil prices and the insecurity of oil supplies has worsened the situation. Therefore, the introduction of environmental sustainability and energy efficiency (i.e., an energy management system) is essential for transportation systems.

In an article entitled “Benchmarking Sustainability Urban Mobility” Miranda [2], believes that a sustainable transport is defined as a system that contributes positively to economic and social welfare without having any negative effect on human health and the environment. She also indicates that in the present consideration of the social, economic and environmental aspects of energy management, the system should be integrated to achieve the following [2]:

- Satisfy the basic needs for access and movement of the entire society while maintaining compatibility with human health and the ecosystem.
- Choose transport modes that have acceptable costs, function efficiently, and can support a dynamic economy and regional development.
- Develop renewable resources at a rate below or equal to their regeneration, develop non-renewable resources at a rate below or equal to the utilization of renewable substitutes, and reduce sound emission and land use to the lowest possible minimum.

There is also a need for significant changes in current transportation systems to increase equity, economic efficiency and environmental safety. Moreover, individual transportation must take second place to long-term strategies that benefit the community.

According to Miranda [2], there are two factors in the energy demand of an integrated transport system. The first one concerns the type of energy source that should be used, and the second one concerns the amount of energy that should be consumed. According to her researches, the world’s total transport energy consumption has increased in recent years, and it is now almost one-third of the total amount of energy consumed in developed countries. Of this total, road transport consumes almost 80%. Railway transport increased by the least amount by only 1.4 times because of the energy conversion of coal to diesel and electric power. According to statistics compiled in 2005, road transport occupied 79% of energy consumption and carbon dioxide emission, while railway transport, water transport, and air transport occupied only 7%, 8%, and 6%, respectively [2].

1.1.1 Problem statement.

Unfortunately, no ultimate benchmarking model has been developed for energy management systems in metro stations. In addition, to ensure the efficient use of energy in metro stations, there is a need to implement strategies for managing energy systems and considering the effects of these strategies on the environment. Also, to confirm the sustainable consumption of energy in metro stations, benchmarking methods should be implemented. Ultimately, a “Best in Class” model of the energy strategies used in metro stations is required to establish a reference for future projects.

1.1.2 Objectives.

The main objective of this study is to develop an approach for benchmarking the application of energy management systems in metro stations. This will be accomplished by the following:

1. Conducting a broad literature review on the techniques available in energy management systems.
2. Creating an optimal design system that uses different energy management elements in metro station.
3. Developing a “Best in Class” system application matrix (SAM) for energy management systems in metro stations.
4. Validating SAM via the input of industry experts (panels or surveys) by using AHP analysis and QFD matrix.
5. Piloting the SAM using theoretical data to develop an integration model to measure the level of success in energy management systems for metro stations.

1.1.3 Literature review.

The literature review investigates metro transit systems and the kind of energy management that has been implemented in this part of the transport systems. The review then will focus on energy management practices in public buildings because metro stations can be integrated into this category. Subsequently, energy management systems in buildings for hot environment such as Dubai will be evaluated to determine the challenges and limitations of energy management. The Analytical Hierarchy Process (AHP) then will be explained as well as and how the judgments of experts can be collected and prioritized using this process. Next, the Quality Function Development (QFD) matrix will be described to clarify the benchmarking methods used in the industry.

1.1.4 Research significance.

Many studies has shown the importance of integrating the energy management system in both transportation and construction sectors. Additionally, 16% of the total consumption of the energy in the world is typically attributed to consumption in public buildings. Metro stations are high traffic publically accessed buildings. Although, there are some energy management techniques that have been suggested to reduce the energy consumption in metro stations, there is no research work on comprehensive benchmarking models for the optimal use of energy management systems in such facilities.

Moreover, metro stations in several countries have applied various energy management systems and techniques, such as energy storage units, platform screen doors…etc. Yet, to the author's knowledge, there is no literature on a metro/train stations that applied a blanket approach to measure and manage energy efficiency. For example, the Paris metro systems (RATP) recently began to retrofit their stations with LED lightings and it is estimated the energy consumption should decrees by almost 50% of total consumption. Some countries such as United Stated, Germany, and Italy are using energy storage units to recover about 8% of lost energy. The UAE installed platform screen doors in metro stations to enhance the safety of the passengers and also reduce the energy consumption by preventing the loss of air to the tunnel.

Thus, this thesis proposed "Best in Class" model of the energy management strategies and techniques in metro stations to be used as a reference index for future projects. The theoretical design of the "Best in Class" metro station benchmarking index validated using via AHP methodology and a QFD matrix was created. The final usable benchmarking model is coined the System Application Matrix (SAM).

1.1.5 Research methodology.

1. Design an optimal "Best in Class" metro station benchmarking index using three main categories of energy management: energy efficiency system, renewable energy system and recovery energy system. Each main category has subcategories or elements, for example, Light Emitting Diodes (LED) lighting, the insulation of walls and platform screen doors are three elements in an energy efficient system. The Solar panel is the only subcategory in the renewable energy system, and energy storage is the only element in the recovery energy system. The optimal design of each subcategory will be provided in this section.
2. Validate the design of the "Best in Class" metro station through an expert panel using AHP analysis to find the priorities of three energy management systems categories. Six professional questioners comprise the AHP expert panel. Three were from the field and three were from the academia.
3. The rating process index and the AHP driven prioritization will be used to create the QFD decision matrix
4. Create a Systems Application Matrix (SAM) using both AHP and QFD results to integrate the integrated benchmarking model for the effectiveness of energy management practices in metro stations.

1.1.6 Thesis organization.

- Chapter 2: Provides a broad review of the literature on buildings and metro transit systems, followed by an explanation of the benchmarking method, AHP and QFD.
- Chapter 3: Specifies the research methodology used in the design, expert panel and QFD methods.
- Chapter 4: Analyses the expert panel data and QFD.
- Chapter 5: Develops the ultimate benchmarking tool (SAM).
- Chapter 6: Provides recommendations and concludes the study.

Chapter 2: Literature Review

2.1 Metro Transit System

A metro system is considered a rapid transport system and is sometimes referred to as a subway or underground. The metro system involves both passenger carriages and disembarking station buildings that facilitate passenger access and exit. At the end of 2010, there were approximately 160 metro systems worldwide [1]. A metro system is defined as an electric passenger transport system that has a high rate of services and a high capacity. The difference between Metrorail and other types of public transport, such as light rail and commuter rail, is not always clear. However, metro systems typically derive from metropolitan transit systems, which are used in metropolitan areas or modern cities. In contrast to a light rail system, a metro system runs on a grade-separated exclusive right-of-way without any contact with traffic and pedestrians [1]. In addition, metro systems do not have any common track with freight trains and inter-city rail services.

According to Wright [1], London was the first city to have an underground mass transit line. It was opened in 1890. Initially, steam was the power supply used in the London metro. Later, the first electric metro opened in the United States in the city of Boston. Since then, 116 countries in Europe, America, Asia, the Middle East and North Africa have opened metro systems in their main cities. Although the investment cost is relatively high, the potential for metro system development is considerable because of the rampant overpopulation of cities. According to Carmen [3], the metro system is one of the most effective transport systems in terms of space occupancy and energy consumption. He also showed in his article that in 2006, metro networks were used to transport almost 155 million passengers per day worldwide to their destinations. The number of passengers in metro systems was 34 times that of the average daily number of air passengers during the same period, which highlights the social and economic significance of developing and operating metro system.

However, the capital costs of rail systems have deterred their further adoption in growing cities. Capital costs include planning, initial construction and technical equipment. Table 1 shows the capital costs of various rail systems. The initial capital costs of metro systems (stations, routes and carriages) depend mostly on the prices of building materials, labor, planning institutions, permit procedures, and geological conditions as well as the extent of grade separation required and right-of-away arrangements [1].

Table 1: Capital Costs of Various Rail Systems [1]

Railway	Type	Cost/Km (US $)	Notes
West Rail Hong Kong	Heavy Metro	220 m	38% Tunnel
Kuala Lumpur-Putra	LRT	50 m	Elevated Driverless
Kuala Lumpur-Star	Heavy Metro	50 m	Largely Elevated
Manila-Line 3 extension	Light Metro	50 m	Elevated
Bangkok Sky train	Metro	74 m	Elevated
Caracas-Venezuela	Metro	90 m	Elevated
Mexico City	Metro	41 m	Elevated

Research has shown that effective planning procedures usually increase capital costs dramatically because they mandate designs that ensure safety [1]. In addition, an assessment of quality is required at each stage of the development of the rail system. Table 2 shows the assessment of factors that affect rail-based MRT capital costs in a European capital city. The operating costs include maintenance, fuel, salaries and so forth. The operation costs are determined by the amount of services required by each metro car. As operating services increase, the circulation time and number of cars needed for single line decrease. There are three main categories of operation costs: per vehicle hours, per passenger trips and revenue per vehicle km.

Table 2: Factors Influencing Metro Capital Costs [1]

Influence	Factors
Dominant	Management/Organization Quality New system, or progressive expansion of existing system
Large	Ground Condition (Underground construction). Urban Constrains and topography (utilities, diversions, proximity, etc. Design and Safety requirements. Depth of water table Financing Cost
Moderate	Land Costs Competition in the equipment supply and construction market
Small	Labor Costs Taxes and duties System features (long trains, AC, special access etc.)

Currently, energy and environmental sustainability is the predominant objective in the design of mobility systems. Because energy falls within both the economic and the environmental dimensions of sustainability, its related economic efficiency should be ensured. In fact, in an economically prudent system, it is essential to demonstrate a high level of energy efficiency [3]. As Figure 1 shows, in consequence of economic growth, transport demand has increased in the European Union (EU) in recent years.

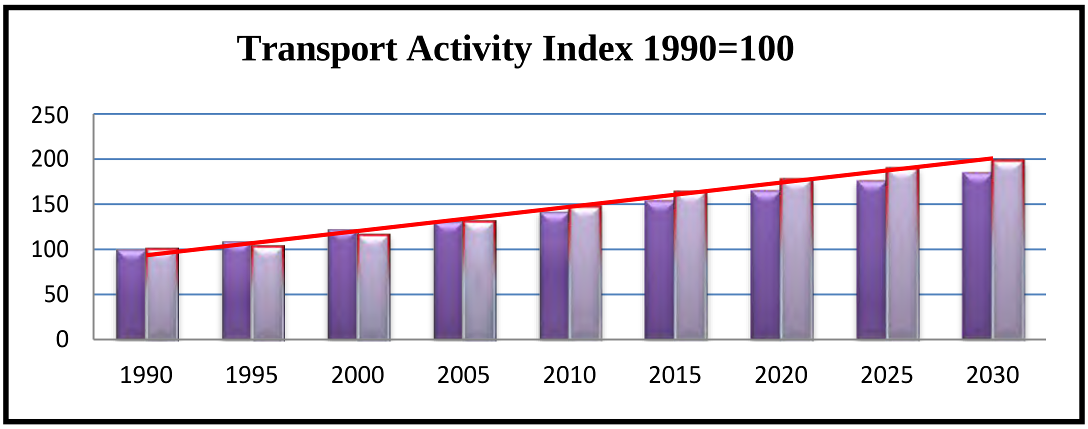


Figure 1: Transport Activity in the EU in Terms of GDP Index [3]

Figures 2 and 3 show the transport sector in the European Union (EU), which is responsible for almost 30% of total energy consumption and 27% of total Green House Gases (GHG) emissions.

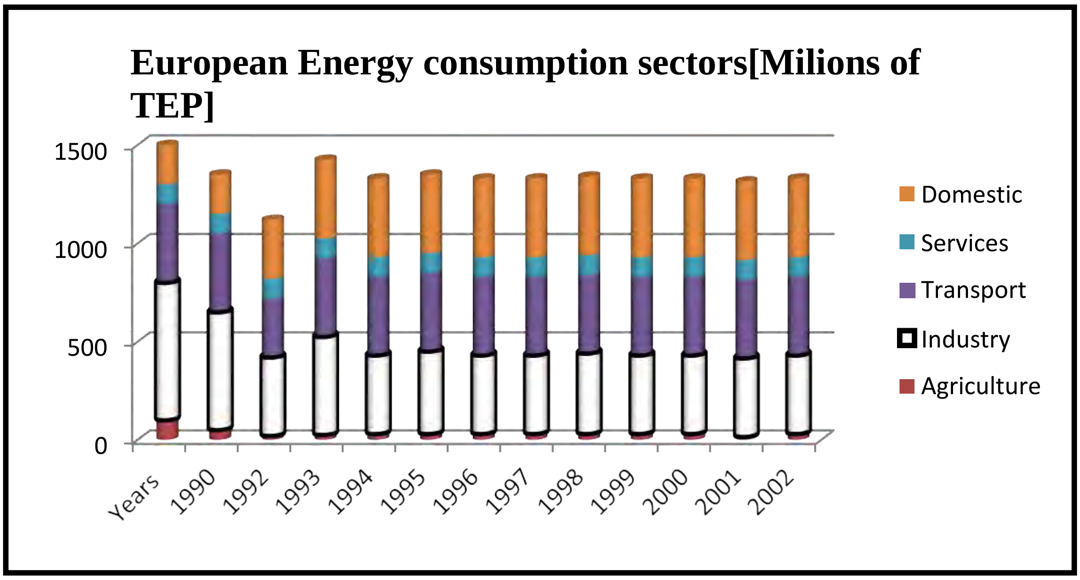


Figure 2: European Energy Consumption Sectors [3]

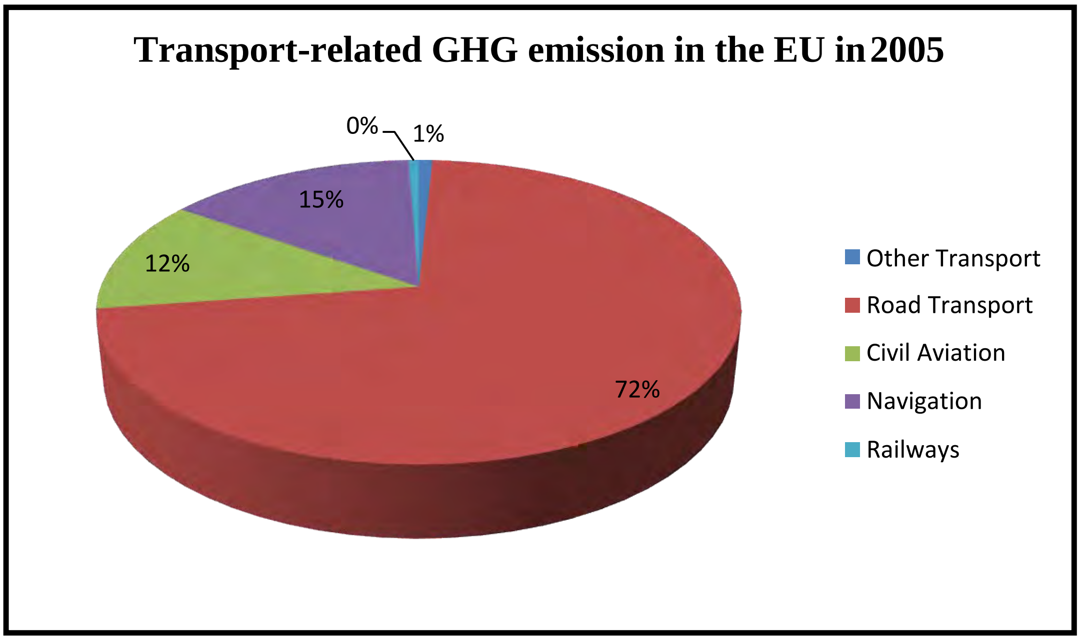


Figure 3: Transport-Related GHG Emission in the EU in 2005 [3]

2.2 Energy Management Systems in Buildings

According to a report entitled “Energy Conservation and Management Plan” [4], energy management systems (EMS) are strategic management practices that require a methodical approach to achieve the maximum energy savings in a building design. The process includes energy conservation, energy efficiency and a system for tapping off-grid renewable resources. Co-generation and natural gas are viewed as slightly more desirable sources of energy compared to hydrocarbons and fossil fuel, which are the least desirable [4].

In an article entitled “Managing Energy Smart Homes According to Energy Prices” Missaoui [5] attested that buildings with advanced energy management systems (BEMS) are actually smart buildings because they implement strategies and ideas to reduce the total energy needed for both construction and maintenances, and they provide users with a more comfortable living environment. The aim of this system is to enhance the ease, comfort and security of the users while reducing the amounts of energy consumption and related waste. Energy management systems provide a method of controlling the consumption of energy by using new techniques that match the energy production required to meet consumers’ needs.

Missaoui [5] also proved that there are two main objectives of using EMSs: to improve energy efficiency and reduce the GHG emissions. EMSs typically fall into two categories: predictive and real-time control models. The predictive control model uses predication to measure the data that are used to find the best strategy for energy management in buildings. The real-time control data are used to implement the system by applying the sophisticated mode to find the best energy management strategy to control the consumption of energy in buildings. Real-time control models also use predictive techniques by establishing real-time algorithms without forecasting price [5]. The aim of these models is to encourage users to control load peaks in order to decrease the peak-to-average ratio (PAR).

Metro rail systems consist of passenger carriages and disembarking stations. This research focuses on the metro station buildings because a large portion of energy is consumed in them. Approximately 32% of the total consumption of the energy in the world is attributed to consumption in buildings and indoor-living habitats, in addition to 36% of GHG emissions [2]. Furthermore, in an article named “China building energy consumption: Situation, challenges and corresponding measures”, Cal [6] showed that the energy consumption of buildings is increasing by more than 10% yearly in China. Also, the total national consumption of energy by 2004 was about 20.7% in buildings. Figure 4 shows the data on energy consumption in China by building type. As you can see in figure 4, public buildings account for approximately 16% of total energy consumption. Public facilities are defined as areas with a gross floor area of more than 20,000 m^2 [6].

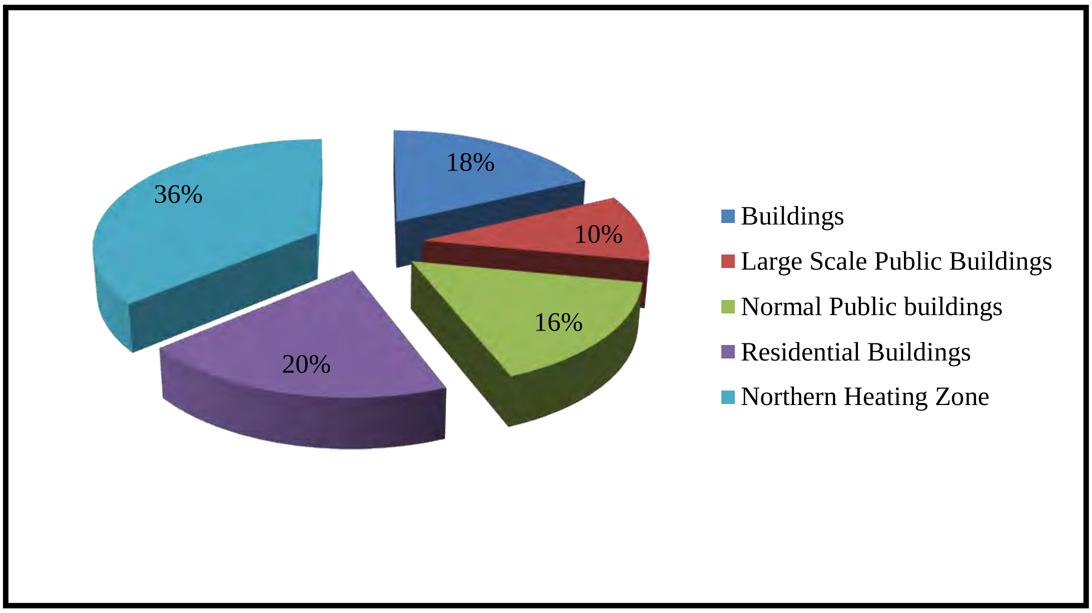


Figure 4: Different Types of Energy Consumption in Buildings in China [7].

Therefore, according to a report entitled "Energy Conservation and Management Plan" by Western Cape [7], there is a need to create high-energy efficiency in public buildings. The following series of strategies could be used:

1. Strong management and supervision of new government projects to instigate designs with energy management in mind.
2. Energy consumption reduction in existing public building by implementing a strong demand side energy (DSE) management in public areas.
3. Installation of powerful systems to encourage energy conservation in buildings.
4. Provided governmental financial incentives to support energy management strategies in new and existing buildings.

At present, lighting systems, air conditioning, heating and power tools are the main energy consumers in modern buildings. According to Cal [6], energy management systems in buildings should address the following aspects:

1. Improve the thermal insulation in buildings via door and window openings, cladding and wall systems.
2. Improve the efficiency of HVAC and lightening systems (cooling, heating, ventilation, etc.).
3. Enhance energy controls in all buildings zones.
4. Expand the use of renewable energy sources.
5. Spread education and awareness about energy conservation.

Energy management systems (EMSs) are more effective if this process starts in the design and renovation of new and existing buildings. According to Western Cape report [7], it is also crucial to ask the following questions to assess the construction of every part of the building:

- Materials: How much energy is needed to transport and construct the building?
- Thermal efficiency: How is the thermal insulation being used in walls, ceiling, roofs, doors and windows to minimize the heating and cooling system of the building?
- Orientation: How is the building orientated with respect to the sun?
- Painting: How will the paintings of the internal and external walls of the building affect the energy consumption by the heating system?

- Natural heating and ventilation system: how does the building use both natural ventilation and daylight?

Another approach to reducing the consumption of grid energy in buildings is to use renewable energy sources. Solar energy systems, ground heat pumps and photovoltaic power generation are the main sources of renewable energy that are appropriate to use in metro stations. Figure 5 shows a hierarchy that energy management should follow in reducing energy demand by first using energy efficiently and then sustaining the remaining energy demand by using cleaner and sustainable energy resources.

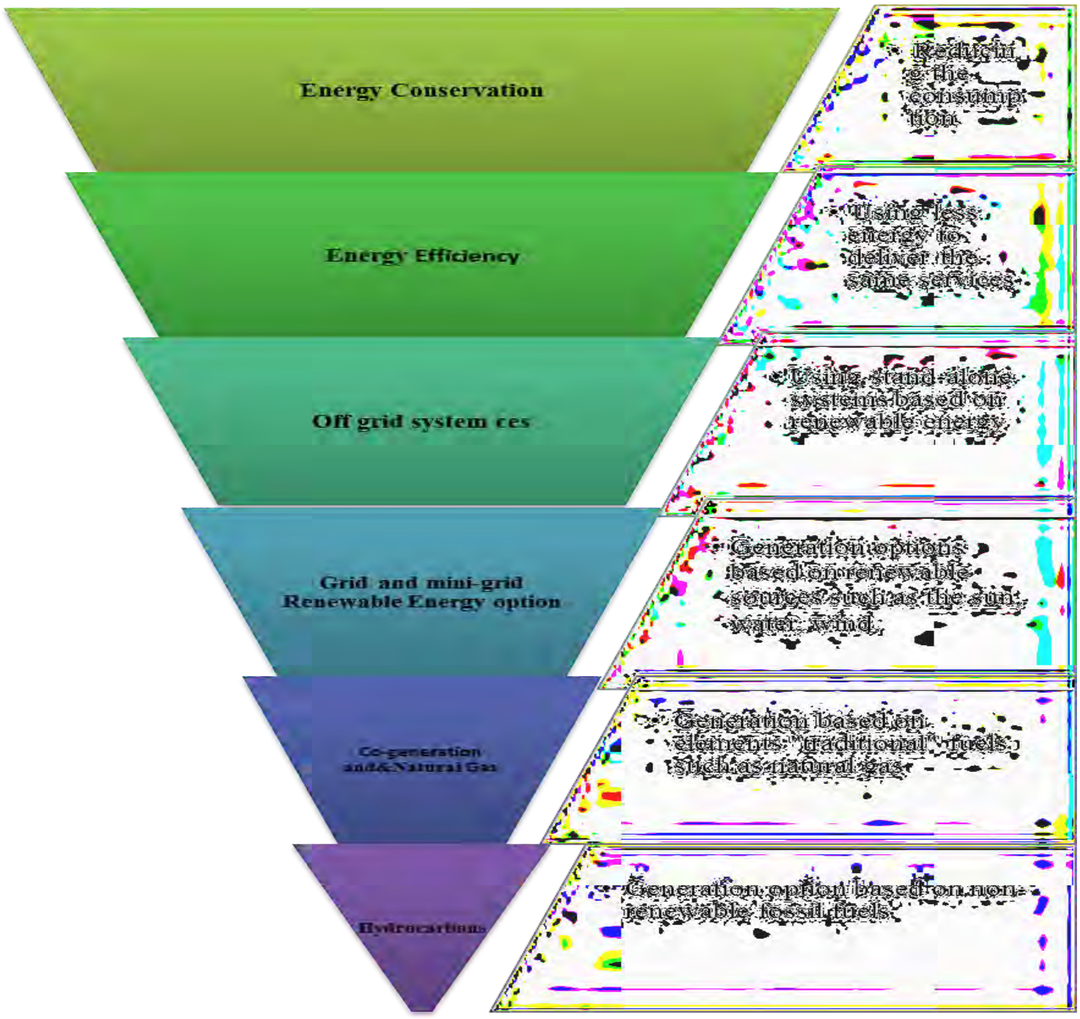


Figure 5: Hierarchy of Energy Management System [7]

2.3 Energy System Management in Hot Environments

Desert-prone hot and humid climates present a challenge for energy management. An overwhelming proportion of energy is consumed by air conditioning to create comfortable environments for work and leisure. Without synthetic weather adjustment techniques and gear, it is very difficult to sustain a comfortable indoor environment that is conducive to work and healthy living. This of course applies to buildings and enclosed environments in the United Arab Emirates (UAE). However, the initial design of a building can still contribute to improved energy efficiency in the long-term usage of the building. According to an article entitled “Modeling Renewable Energy Readiness: The UAE Context” by Choucri [8], recently, more attention has been paid to demand side energy (DSE) management, which means that consumer demand is controlled by applying various incentives and techniques to trigger users to reduce their energy consumption. This is facilitated by some EMSs that focus on heat, ventilation and air conditioning (HAVC) and electrical water heaters [8]. According to an article named “Solar power in building design: the engineer's complete design resource” by Gevorkian [9], HAVC systems use thermodynamic mechanical designs with fluid mechanics and heat transfer to achieve indoor environmental comfort. Because HVAC systems constitute a major portion of energy consumption in enclosed environments in the UAE, DSE could constitute a plausible approach for further integration in the methodologies used to benchmark energy consumption by metro stations. Gevorkian [9] also believes that the present study proposes the photovoltaic power source (PV) method of energy management. In the PV method, semiconductors are used to convert solar radiation directly into current electricity to generate electrical power through the solar panels in roofs or underground. There is an emerging trend towards energy management in the UAE. Both governmental and social levels have realized that it is necessary to reduce energy costs and developed ways to increase the efficiency of energy use.

The UAE has a considerable number of potential resources, such as petroleum and gas, compared to its small population. It is considered one of the highest exporters of petroleum byproducts. The awareness of energy efficiency is increasing, and energy regulations are soon to follow. Chourcri [8] also believes that the mounting inclination to implement such policies should have two applicable results. First, it will direct the country towards cleaner production schemes, and it will inspire it to be a leader in the sector of energy management systems. Second, it will inspire organizations to design according to the need for sustainable energy. Additionally, Abu Dhabi is trying to save latent resources, such as fossil fuel reserves, for future generations by investing in the renewable energy market in order to meet today's energy demand and the possible future rise in local demand.

The emirate of Abu Dhabi, which is the ruling capital of the UAE and the seat of government, defined and spearheaded these new energy policies. According to the "Energy management" report by Masdar's second sustainability group [10] , the goal is to move toward a symmetric system for renewable energy and secure 7% of the energy demand by using more renewable energy resources by the year 2020. Moreover, possible strategies are being explored to balance the production of energy by using both renewable and hydrocarbon resources. Nevertheless, according to Choucri [8], the renewable energy policy in UAE would be effective if the regulations were mandatory in the implementation of operational systems in all governmental organizations in the UAE. Moreover, energy efficiency should be seen as not only a basis of project validity but also a strategy for better energy management in every aspect of projects in the UAE.

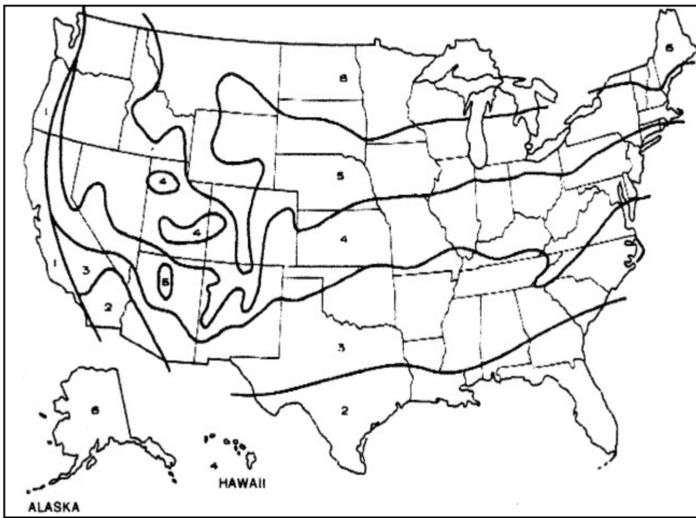
2.4 Elements of Energy Management in Metro Stations

The following sections describe the best practices for the energy management processes used in metro stations. The sections provide a brief description of each energy management subcategories, including their advantages and disadvantages.

2.4.1 Insulation of walls.

The insulation of walls, floors, and roofs is an important factor in improving energy efficiency. As awareness of the needs for energy efficiency increases, the needs for insulation also rise. The remaining concern is the optimal choice of materials that work the best in different climates and building designs. According to Insolent fiberglass report [11], insulation helps to reduce the heat loss and the formation of moisture pockets. Insulation should be relatively cheap, durable and environmental friendly. The optimum thickness of the insulation is determined by the climate in which the building is constructed and the desired level of energy efficiency. Figure 6 illustrates the minimum thermal resistance of insulation by climate zone in the United States. Polystyrene and rockwool are known as the most effective insulation materials. Polystyrene is a rigid plastic material and has a very lightweight compared to other types of insulation. Although it is a lightweight material, its compressive strength and block rigidity is impressive. It is available as both expanded polystyrene (EPS) and directly extruded polystyrene (XPS) [12]. Rockwool insulation is a fire-retardant material and has long-term thermal performance in different parts of buildings. It is considered the most sustainable insulation material. It has dimensional stability, and it reduces the sounds and moistures [13]. According to both Kamstrup [13] and Yucel [12], some advantages of using both polystyrene and rockwool insulation are listed as follow:

- Energy efficient: reduces the energy demand and heat transmission
- Neither non-destructive nor structurally intrusive: does not trigger damage to adjoining materials, and it can preserve structural reliability.
- Sound proof: reduces or dampens sound transmission.
- Light weight: controls dead loads on structures
- Easy to handle: both materials are easy to handle, install and assemble on site.



RECOMMENDED MINIMUM THERMAL RESISTANCE (R) OF INSULATION

ZONE	CEILING	WALL	FLOOR
1	19	11	11
2	26	13	11
3	26	19	13
4	30	19	19
5	33	19	22
6	38	19	22

Figure 6: Minimum Thermal Insulation Resistance for Different Climates [13]

2.4.2 Solar systems.

In a report entitled “Solar Ready Buildings Planning Guide”, Lisell [14] attested that the demand for renewable energy has increased because of the need for energy efficiency in all types of buildings. According to his researches, the photovoltaic arrays and solar cells are the third most important type of renewable energy technologies after the hydro and wind power. She also mentioned in her report that this type of renewable energy captures the energy from the sun by using photovoltaic cells, which is why it is also called solar photovoltaic renewable energy. Photovoltaic energy sources can be utilized to cover lighting and heating systems in metro stations, in which the energy captured from sunlight is converted to electricity by using the photovoltaic cells [14].

This kind of renewable energy is ground-mounted and installed in either the roof or the wall of a building. The present study focuses on the installation of photovoltaic energy panels in the roof of a metro station. Furthermore, because silicon is a semi-conducting material, it is used to build the layers of solar panels. The electric field in the layers will be produced as the sunlight shines on the photovoltaic cells. The rate at which the PV cells generate energy is measured in kilowatts peak (kWp).

Li [15] showed in his article named “BISE Design in Solar-Powered Residential Building”, several factors affect the cost of the installation of solar panels, such as the following:

- ❖ Higher cost and greater energy saving are associated with solar panel devices because they can produce a large quantity of electricity.
- ❖ More cost-effective strategies are associated with the larger systems that produce energy, compared to smaller systems.
- ❖ Higher cost is associated with the panels, which are built in the roof, compared to panels that are built on the ground.

In hot environments with constant sunshine, such as the UAE, utilizing solar energy in buildings is a prudent choice. However, choosing the appropriate solar device can be challenging. According to Li [15], a solar energy photo-thermal system has two key systems: active and passive. Passive systems are easier because they are independent of additional devices for heat transfer. The design of the building should be considered carefully before deciding on a solar energy strategy. To achieve the best efficiency from solar radiation systems, several elements, such as the selection of building materials, layout, interior spacing and exterior setting, are crucial. On the other hand, active systems are complex and relatively higher in cost compared to passive systems. For full functionality, additional gear, such as solar heating kits and power assemblies, are needed.

Li [15] also shows that in passive solar-powered systems, solar energy can be received in two different forms: heat storage wall and direct gain. Windows are the key element in solar heat storage. For instance, in cold climates, it is important to use large windows and double-glazed low emissivity glass. However, in Middle Eastern countries, the weather is extremely hot and humid from May to October. Thus, it is very important to install elements, such as sun shading boards, to prevent the entrance of solar radiation into overheated interiors. There are many options of shading boards on the market, each having different characteristics. Figure 7 shows a typical thermal heat storage technique for a south wall with double deck glass curtain cover. An air layer is formed between the wall and the glass cover. Once the heat is received from solar radiation through the glass layer of the wall, it will be evenly transferred to the interior surfaces of the building.

Furthermore, Li [15] indicates in his article that in an active solar system, solar radiation is received through external solar heating and power collection equipment. These panels are usually placed on the roof and side slopes of the building. As shown in Figure 8, this system is composed of two fans: a collector fan and a heating fan. Both run concurrently to circulate air through the thermal energy collector. These two fans can also be used as an outlet solar collector to provide hot water. On summer days when heat transfer into the building is not desired, an electric fan can be used to control the airflow further.

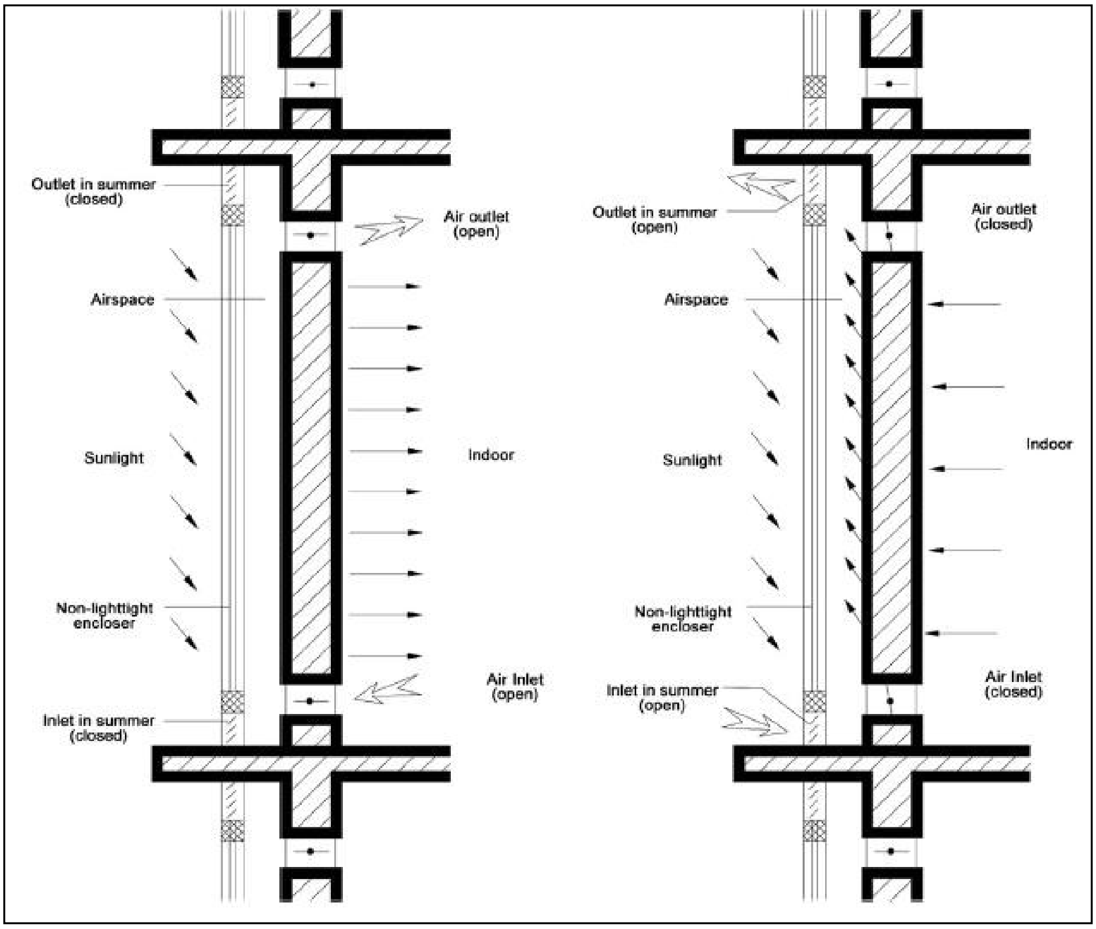


Figure 7: Solar System Power [15]

In this system, a thermal storage room should be used to collect and store the heat for future demand. On sunny days, solar energy can be collected and stored. When the electric fan and the heating fans are switched off, the collector fan will be turned on to gather heat from the solar radiation, and the hot air will flow into the heat storeroom until it reaches its maximum storage capacity. On cool days, the heating and electric fans are switched on [15]. The cold air inside the building flows through the gravel layer in the heating room, and the warmer air is transferred inside the building. When the heating system is not needed for the building, the solar collector can be used to supply hot water for bathrooms and retail use.

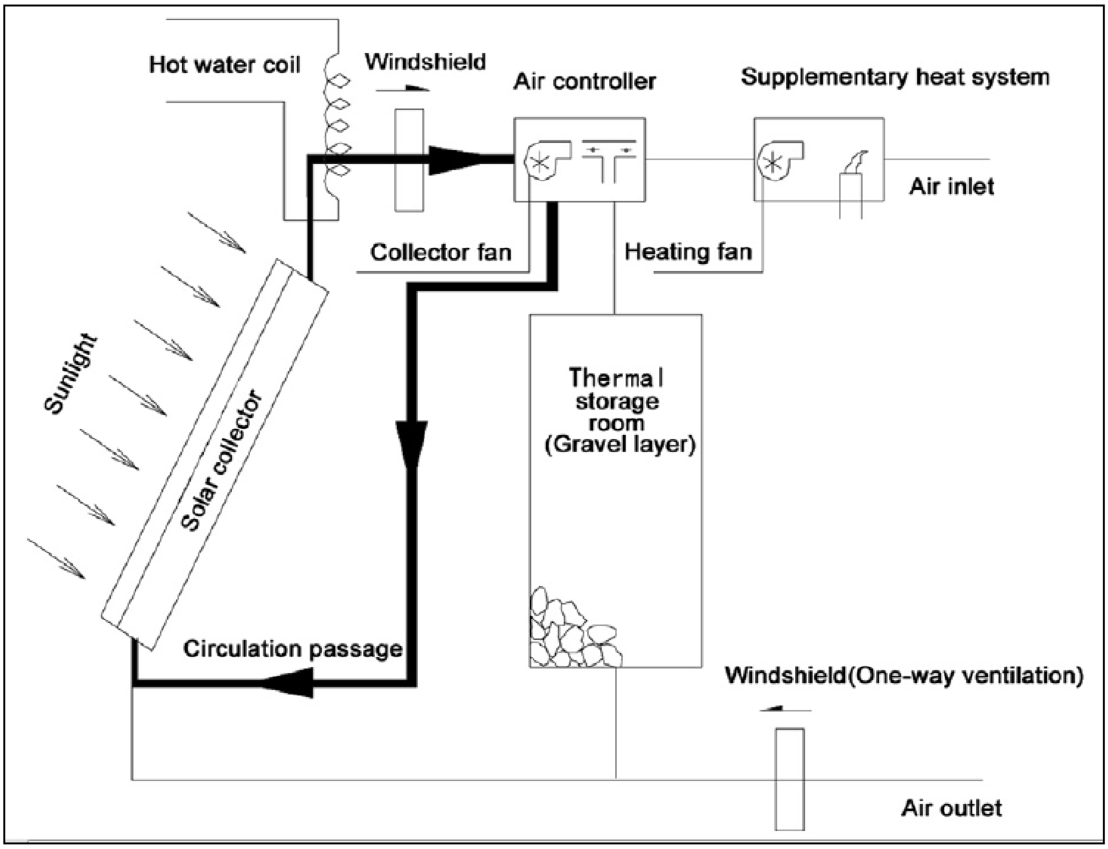


Figure 8: Solar Heating System for Providing Hot Water [15]

2.4.3 Platform screen doors.

Platform screen doors can be used as both a passenger safety measure and a temperature control mechanism inside a metro station. The safety aspect has been addressed in many ways, including open and closed screens. According to a journal entitled “Review of Platform/Train Interface Protection System on Railways”, by Connor [16], the PSD is a relatively new technology. It was developed in 1960 and first installed in 1973 at the Dallas/Fort Worth International Airport (DFW). The purpose of this technology is to isolate the station platform from the railway track. The metro station’s doors interact with these PSDs, and they open and close automatically when the trains enter the stations.

Recently, concerns about loading and unloading passengers safely in a metro station have been viewed more seriously than they were previously. Several metro stations use a simple platform with stairs attached to allow travelers to ascend to a coach in order to board [16]. Other transport systems, such as the London tube, include built-up platforms about the same height as the metro floor, which offers easier access to the coaches. An increase in the use of metros, better safety approaches, sustainability awareness, and many other factors have forced metro designers to develop a system that physically separates passengers from the railway track and the train.

Furthermore, Connor [16] attested that this system contains fixed barriers or sliding powered doors and is referred to as the platform screen doors (PSD) system. One of the main functions of PSD is to protect the passengers on the platform from falling onto the railway track, but they also help to control the temperature in metro station buildings. There are three types of PDSs: full-closed, semi-closed (platform edge doors or PED) and half height. The simplest protection for platforms or trains consists of fixed barriers or half height doors. In addition to indicating the locations of metro doors, these provide protection to some degree, but they cannot completely prevent people from falling onto the railway tracks. The drawback of such barriers is that there is a large gap between the train and the screens, which could result in trapping a passenger. The platform edge doors (PED) provide a complete separation between the railway track and the platform. However, they are semi-closed and hence do not completely seal the railway track from the platform. Although PEDs are full height and enhance safety, they are not meant to control climate or to prevent the air loss in the station, which is the main difference between these and the semi closed system [16]. As Figure 9 shown, the fully closed PSDs provide a total separation between the track and the platform, thereby controlling the climate and providing enhanced safety. In addition, the humid air existing in the tunnel is prevented from entering the station, which leads to a reduction in cooling load, thereby reducing energy consumption. They control climate and reduce energy consumption by preventing the loss of air in train tunnels. Moreover, enclosed PSDs detach the platform from the dust, heat and air blast generated by train movement.

2.4.3.1 Features of using PSDs.

According to Connor [16], several advantages for PSDs are associated with using this type of technology in metro stations, such as improving the safety by preventing the passengers from falling off the platform or attempting suicide, increasing punctuality and reliability, enhancing the heating, air conditioning, and cooling of the station by removing the station from the tunnel, which increases energy efficiency, increasing economic efficiency by removing the motormen or conductor because of automatic train operation, reducing the pressure felt by passengers when the trains arrives, reducing the dispatch time of trains, and permitting trains to enter stations at relatively higher speeds.

Figure 9: Fully Closed PSD in Dubai Metro Stations

2.4.4 Flywheel energy storage.

In a report entitled "Energy Storages Technology Review", Bradbury Corporation Company [17] stated that because energy storage is an important conservation issue, it is taken into account in dealing with railway systems. They also show that energy storage devices are mainly used to enhance poor voltage regulation and improve efficiency by capturing the energy generated by the brakes in trains. Energy devices that are stored on board the trains reduce the acceleration currents by providing an additional power source, thus yielding a reduction in voltage sags. This benchmarking framework contemplates the use of flywheel technology as a type of energy storage device. In an article entitled “Flywheel energy storage-An upswing technology for energy sustainability” Haichang and Jiang [18] indicated that flywheels consist of a disk rotating around an axis that storages kinetic energy generated by angular momentum. The energy generated by motors when a train brakes enters the environment as heat. The flywheel device, which is deployed next to the track, collects and stores this lost energy in the form of kinetic energy. The flywheel releases the energy stored via electrical cables to the motors when the train is about to move away, which results in a power boost. When the energy (charge) is added, the speed of the flywheel increases and then decreases during discharge. Flywheel devices are characterized as follows [18]:

- ✓ Low Speed (less than 10,000 rpm): usually made of considerably heavy disks. These types of flywheels have either vertical or horizontal shafts and consist of magnetic bearings.
- ✓ High Speed (above 10,000 rpm): because these types operate at higher speeds, they require stronger materials, such as composites of graphite or fiberglass, in order to avoid failure. For the same reason, they must have vertical shafts and magnetic bearings.

As shown in Figure 10, Flywheel technology increases the energy recovery system because it prevents energy loss and instead stores it in the form of kinetic energy. However, the key to improve the efficiency is to reduce the friction. In a report entitled “Energy Storage Technologies & Their Role in Renewable Integration”, Oberhofer [19] suggested that in order to achieve a reduction in friction, two things may be considered: 1) create a vacuum in the disk so there will be no air friction; and 2) make the spinning rotor float by placing it on permanent electromagnetic bearings. A modern single flywheel can have speeds of up to 16000 rpm and produce 25 KWh of energy. The William Engineering Company in Singapore believes that boosting traction power is the key factor in increasing the reliability and capacity of railway systems. They suggested adding a power source to the train’s traction motors to achieve this goal. This modification leads to voltage reduction and less power in electrical networks.

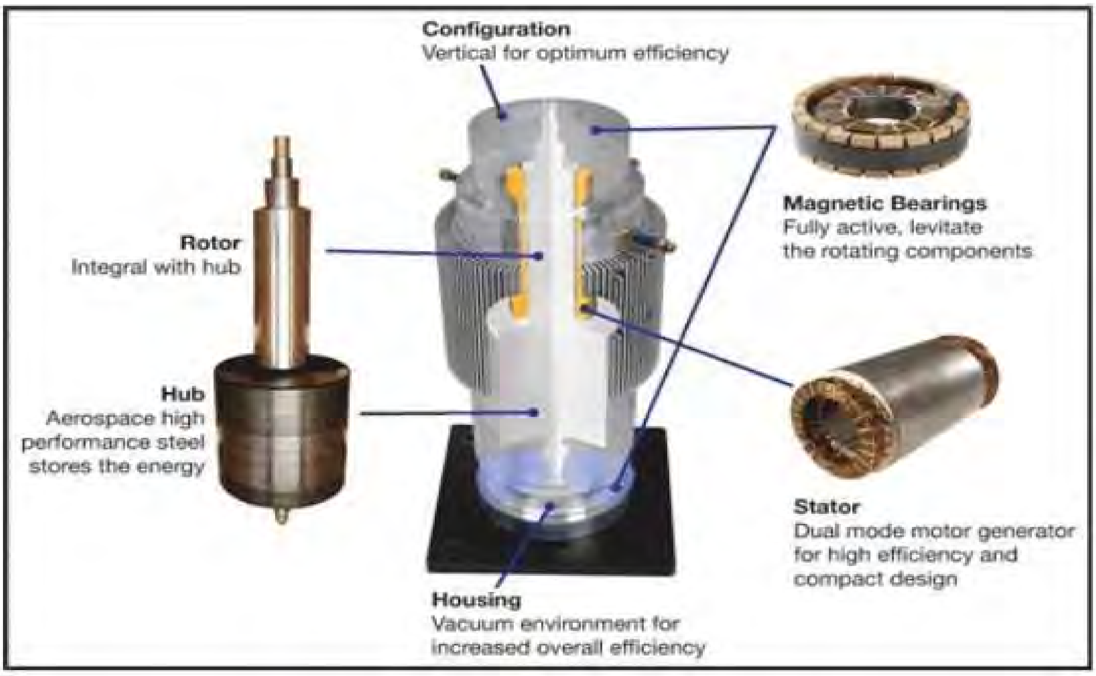


Figure 10: Typical Flywheel Device [17]

According to Bradbury Corporation Company, further advantages of the flywheel system include the following:

- Long lifespan
- Low maintenance
- Environmentally friendly (almost no carbon emission)
- Fast response times
- Improved reliability and performance

And they also showed that the main drawbacks of the flywheel system include the following:

- High acquisition costs
- High self-discharge
- Low storage capacity

Many studies such as Energy Storages Technology Reviews have proposed energy management techniques in trains by using reformative braking, which can be considered one of the main parts of supply in a network of overall energy, especially in trains that constantly negotiate curves and slopes. The energy recovered by supplying an electrical system plan and driving the train can be used in three different ways [17]:

✓ Serving other trains running on the same track

- ✓ Sorting in a storage system or onboard
- ✓ Serving the primary supply network in case of the availability of bidirectional conversion station

On the other hand Ciccarelli [20] believes that the problem of heat production, such as in metro transit in an underground environment, should be considered in the construction of a metro system. To guarantee the level of comfort for both workers and passengers, the construction of over-sized tunnel and station fan plants is needed, which leads to additional power consumption. Hence, stationary storage for braking energy management should be introduced in metro transit systems to ensure comfort concerns and save energy. The advantages of using these stationary stations are as follows:

1. In the case of emergency issues, such as failure and main power supply, they serve as an external source that can help trains to reach the nearest station.
2. They save the investment cost of power system by shaving the power peak.
3. They decrease losses and improve power quality by having a better voltage contour on the power line.

Moreover, Ciccarelli [20] proved that the development of a new generation of batteries has assured higher specific energy (100-1000 Wh/kg), higher specific power (1000 kW/kg), longer lifetime, lower environmental impact and price and better performance, compared to the first generation of batteries, which was introduced in the 1990s. Clearly, the characteristics of the metro line, such as the layout of the power system, traffic scenarios and types of trains could guarantee these results. In recent years, three storage technologies have been established: advanced electrochemical batteries, hydrogen, and flywheels. They vary in cost and performance. Flywheels and supercapacitors (SC) are the most appropriate storage systems because they have more than 106 cycle numbers and power densities over 5kW/kg [20]. Hence, power density and number of charge-discharge cycles could be considered essential factors in metropolitan railways because of the many stops that trains make during a day. The total amount of energy storage system (ESS) in the supercapacitor (SC) energy storage device, which is installed onboard metro trains, is equal to the number of traction inverters.

The kinetic energy of the vehicle can be collected in supercapacitor (SC) devices during the braking phase in a rapid transit train's traction cycle [20]. Therefore, these SCs are recharged to their original state of charge. Supercapacitors (SC) are then able to transfer energy along with the main electrical substation in the successive acceleration phase. Lastly, during the moving phases, the SC becomes idle. It should be noted that the electrical energy involved in this process differs from the variation in kinetic energy caused by energy loss [20]. The following case study has been used to explain the consequences of using energy storages in Rome metro stations and how these systems can help in energy efficiency and recovery systems.

2.4.4.1 Case study.

Case 1: The first case study is the metro-transit system in Rome. It includes Line A and Line B. Line A, which is the object of this study, is 18.76 km long, has 27 stations and its layout contains many curves and slopes. There are six main electric sub-substations (ESS) in the power system. The conversion group of each station has the voltage output of 1.5 kV DC to supply traction lines, and it is equipped with AC/DC with a nominal power rating of about 3.5 MW. In 2002, the metro line in Rome programmed a change in the fleet by introducing new vehicles with larger energy consumption because of the larger nominal power. These new vehicles were MA300, having Bombardier drivers and allowing for the saving of braking energy. The total braking effort of these trains is constant with the value speed of train mass, so the acceleration is expected to be constant as well. The drivers can drive only on minimum speed because the two components are balanced by an onboard computer, which renders the electric braking power useless. By considering all traffic scenarios, some simulations were conducted regarding the system energy performance of the metro line in Rome. The frequencies of the trains and the minimum speed, which nullifies the electric braking power of the train, are two important factors for evaluating this case. In these simulations, only MA300 trains are included, and the constant stop in each station was chosen at 20 seconds as the medium value. The value of the minimum speed of the traffic scenarios is as follows:

- 10 km/h (simulation's name is TS-X and CASE-10)
- 20 km/h (simulation's name is TS-X and CASE 20)

Software (which is explained later) was used to calculate the total amount of the trains' energy consumption, the total ESS energy supply, and the recovered braking energy. The evaluations of some important percentages are as follows:

1. ES% is energy saving percentage [21]:

$$ES\% = E_{ESS}^{WREC} / E_{ESS}^{W/O REC} x100$$

- E_{ES}^{WREC}= Supply energy by ESS with recovering braking energy
- $E_{ES}^{W/0 REC}$= Supply energy by ESS without recovering braking energy

2. ER% is recoverable braking energy [21]:

$$ER\% = E_{TR\ REC,ED} / E_{TR\ REC,BLE}$$

- $E_{TR\ REC,ED}$= Effective recoverable braking energy
- $E_{TR\ REC,BLE}$ = Potential recoverable braking energy

3. ER% is effective recoverable energy with respect to the total energy needed by trains [21]:

$$ER\% = E_{TR\ REC,ED} / E_{TR\ REQ}\ x100$$

- $E_{TR\ REC,ED}$= Effective recovered energy
- $E_{TR\ REQ}$ = Requested energy by the trains

Histograms and curves were plotted to summarize the simulation results. The histogram in Figure 11 shows that the total energy needed by the trains was reduced and the frequency of trains was increased. In addition, by increasing the train frequency to 30, the following results were obtained:

- The energy that was supplied by ESS was reduced by approximately 8%.
- The potential recoverable braking energy was reduced by 4%.
- The effective recoverable braking energy was reduced by 4%.

As shown in Figure 11, by changing the frequency from 120 sec to 600 sec, the following results were obtained [21]:

- ES% was reduced from 38% to 30%.
- ER' was reduced from 95% to 77% and ER'' was reduced from 34 % to 27%.

We can conclude from these results that when there are few trains, the potential braking energy to be recovered is small, so the energy received by the line capacity is reduced and the energy saving is reduced.

Lastly, one of the most important methods used in energy management, which can save energy approximately 30% to 38% in a metro transit system, is to introduce stationary storage in the system. This recoverable braking energy can be used to recharge BEV or PHEV batteries.

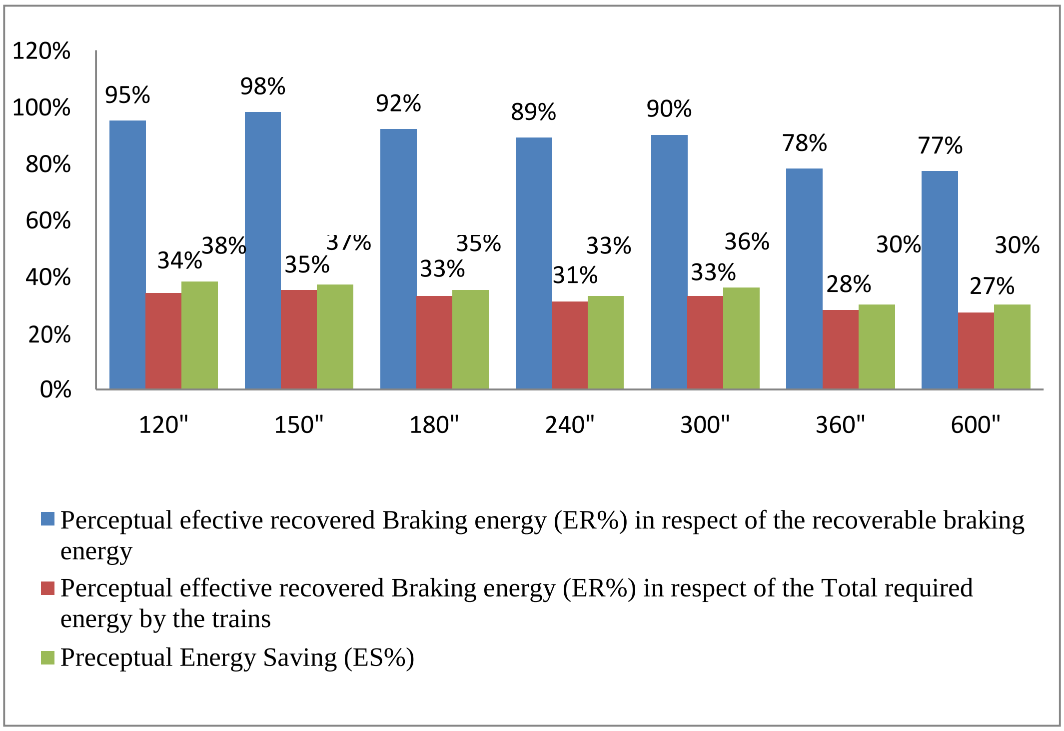


Figure 11: System Energy Values in Percentages [21]

2.4.5 Innovative lighting systems.

Lighting systems are other important factor that needs to be taken into consideration in the design of metro stations. It also proved that the lighting systems are the main source of power and energy consumption and they have relatively high initial and maintenance costs. Moreover, metro stations operate for long hours, including many hours after sunset. They are designed and constructed with many parts underground, which lack vital access to natural light. This increases the demand for integrated and innovative lighting systems. Because lighting is a vital part of the basic architecture of most metro stations, it should adhere to the design requirements of the location. Lighting should be efficient, easily maintained and durable.

Light emitting diodes, or LEDs are the most common lighting solutions used in residential and commercial spaces. According to a report entitled “LED Lighting Technology – Insights” by Patent iNSIGHT Pro group [22], LED lighting systems are more energy efficient than other systems are, and they tend to have longer lifespans. The main drawback of LEDs is their relatively high initial and renewal costs, but these are compensated by much lower energy usage.

The Paris metro systems (RATP) recently began to retrofit their stations with LED lighting. Authorities are planning this to be the first transport network to use LED lighting 100% of the time. It is estimated that lighting power consumption is responsible for 19% of total energy consumption at RATP. Planners at RATP forecasted that switching the current lighting system to LED lamps should decrease energy consumption and related GHG emissions by 50% across their networks [22]. Furthermore, lighting product manufacturers, such as Schréder, offered a lighting upgrade solution to Brussels metro stations using ASTRAL LED lamps that proved to decrease energy consumption by almost 50%. These lamps also reduced the GHG emissions (CO2) by approximately 20 tons per year. A report by Sandahl for the US Department of Energy provided the following reasons for using LED lighting systems in commercial buildings:

- Energy saving
- Better total system efficiency
- Enhanced luminary optical efficiency
- Control capability
- Decreased maintenance cost
- Enhanced uniformity
- Environmental friendly

LED lights, which are light-emitting diodes, are used to increase the efficiency and durability of lights. They are a solid-state form of lighting that includes some tiny capsules or lenses in which small chips are located on heat-conducting material. Several features are associated with this type of technology, which are discussed below [22]:

2.4.5.1 Size and efficiency.

Because LED lights are usually small in size and low in profile, they can be located in tiny spaces such as light bulbs. They also save more energy compared to incandescent and fluorescent bulbs because they emit light in a specific direction and do not waste energy by giving off light in all directions.

2.4.5.2 Durability.

The definition of a lifetime in lumens is the average number of hours until 70% of initial lightness fails. The lifetime of an incandescent bulb ranges between of 750 and 2,000 hours, and the lifetime of a fluorescent (compact) bulb ranges between 8,000 and 10,000 hours. However, the lifetime of a LED bulb ranges between 35,000 and 50,000 hours, to which is attributed its high durability and long usage.

2.4.5.3 Less waste of energy in heat.

One of the most inefficient usages of energy by the conventional light bulb is by heat. However, LEDs waste little energy in heat because they remain cool. If heat increases due to the energy wasted by bulbs, the load used by air conditioning will increase in the summer. LED bulbs consume only 25% of the electricity needed by an incandescent bulb. Because they emit light in only one direction, less energy and light are wasted. Another important feature of LEDs is that they do not have glass components, which leads to resisting vibration or breakage. Figure 12 shows the LEDs lightings system in Dubai's Metro stations.

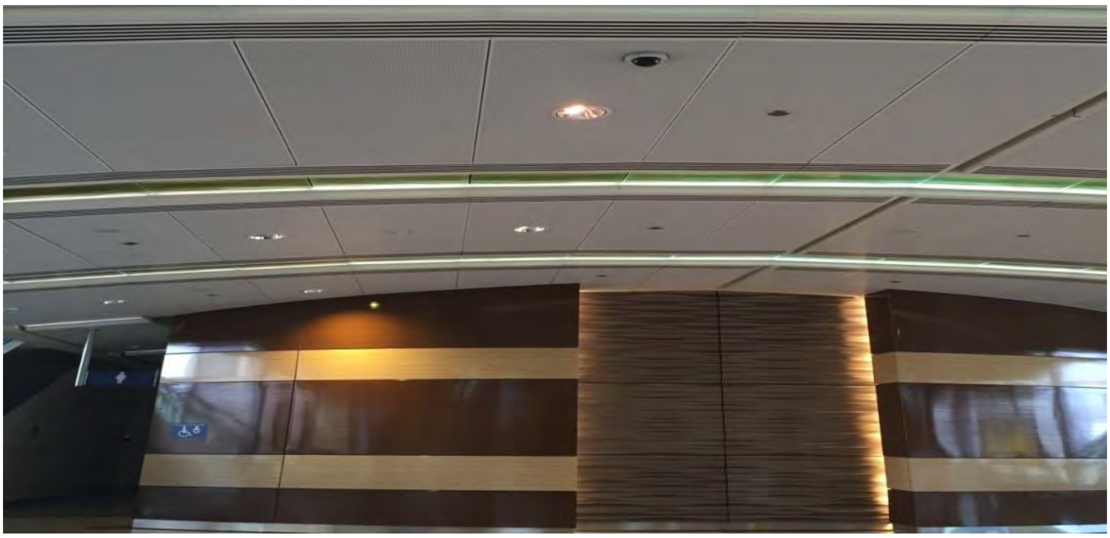


Figure 12: LED Lighting System in Dubai Metro Stations

2.5 Benchmarking Methods Used in Industry

It is necessary to implement effective strategies to ensure the sustainable and efficient use of energy in metro stations. However, such strategies should consider the effects on the environment. The benchmarking of energy efficiency in metro stations could be helpful in achieving this goal. In an article entitled "Review of Building Energy-use performance benchmarking method" Chung [23] believed that benchmarking helps to compare successful strategies used for increasing the energy efficiency of one metro station to those used by other stations. He also proved that in order to benchmark energy efficiency, indexes need to be built to show that the target goal in using an energy management system is to maximize energy efficiency in metro stations. Because of the unlikely performance of a station's energy efficiency, several factors should be taken into account: 1) weather conditions; 2) physical factors, such as the age of the station and the number of floors; 3) the number of occupants on a daily basis. The above factors should be taken into account in normalizing the reference station. In the scope of the present study, benchmarking information is important because it can be used to improve the poor performance of energy efficiencies in some metro stations. It could be helpful for right management practices to have the best performance in energy saving. In addition, it provides competition between companies to improve their performance in energy efficiencies and to know their weaknesses. Two systems are used for benchmarking: an internal system and a public system. Simple normalization (simple), ordinary least squares (QLS, or simple regression analysis), stochastic frontier analysis (SFA), data envelopment analysis (DEA), artificial neural network (ANN), and the model-based method (simulation) are six benchmarking methods used to determine energy efficiencies in buildings [23].

❖ Simple normalization (simple): In the simple normalization method, benchmarking depends on a simple performance sign that has ratios between single input and aspects of output. This performance sign comes from the normalization of energy use, and it depends on the operational hours or the floor area. The energy consumed by stations and the floor area could be used to estimate the energy use intensity (EUI). The unit is kWh/ft^2 or MJ/m^2. After calculating these EUIs, the benchmarking table can be constructed to estimate the input/output ratio.

- Ordinary least squares (OLS): This method helps to find the linear regression model by finding the regression line, which shows the average level of energy efficiency. The average level shows that stations above the average level have energy efficiencies in their systems. Stations below the average level have energy inefficiencies in their systems. In addition, the distribution of residual energy, which is the difference between the actual EUI and predicted EUI, can provide the benchmarking system for the regression model. Hence, if the EUI of any station is less than (negative) the EUI of predicated station, its energy system is inefficient.
- Regression model: If the factors of $x_1 \ldots x_p$ are considered the function of linear EUI, the following formula for OLS can be identified. The factors of $x_1 \ldots x_n$ are consistent for which EUIs are normally climate adjusted [23].

$$min_{a,b,\varepsilon}\{\sum_{i=}^{n} \varepsilon_i^2 \,|EUI_i = a + b_1x_{1i} + \cdots + b_px_{pi} + \varepsilon_i \forall_i = 1, \ldots . n\}$$

- a = intercept
- $b_1 \ldots\ldots b_n$ = slope
- $x_{1i} \ldots\ x_{pi}$ = factors such as which kind of energy system used, how big the floor area, how many years the age of building, and so on.
- ε_i = the random error for the i^{th} observation

- Variant of the ordinary least squares method: The regression model in the previous section was benchmarked poorly for the EUI mean because of the skewed distribution of the indicators. To eliminate this effect, it is better to use the standard deviation for the regression model to create a table of the benchmarking results, which improves the consistency of the results because it covers the effect of outliers. In order to calculate the predicted EUI and in order to construct a table of the distribution of percentiles (i.e., benchmarked table), the best-fitted regression model should benchmark a specific station. This percentile or benchmarked table is estimated by the distribution of standard deviation mean. The benchmarked table then can be used as a basis of comparison between the actual EUI and the EUI provided by the table. The following formula shows that the standard error (SE) can be used to find the approximate distributions of the benchmarked table [23].

$$EUI_{Actual} - EUI_{predicted} \approx t * SE$$

- SE = standard error
- t = value is found in the t-table for each estimation

❖ Another benchmarking process was built by Chung [23], in which a standardized energy efficiency indicator is found by removing the effect of nonconformity in significant factors, such as building characteristics. One of the disadvantages of using OSL is the residual (actual-predicted) measure because of its inefficiencies. Data errors lead to ineffective estimations of the relative efficiency level. Then, by using the following formula, the EUI_{norm} will be calculated [23]:

$$EUI_{norm} = EUI_0 - b_1x_1 - \cdots - b_px_p$$

❖ Data envelopment analysis (DEA): This method provides effective units for every ineffective decision making unit (DMU). It can be used to enhance the benchmarking.

❖ Corrected ordinary least squares (COLS): To overcome the weak points in OLS, Chung suggested using the corrected least squares method, which two stages. In the first stage, the regression line is estimated by using the OLS and then it moves down to cover all data in the regression line [23]. The difference between the actual and estimated EUI is positive unless the station has energy efficiency, in which case the residual is zero.

2.6 Analytic Hierarchy Process (AHP)

The analytic hierarchy process is one of the most well-known methods in the industry that is used in multi-criteria decision making based on how well each alternative’s rate counters the weights and structure of the decision model. Each criterion is weighted according to the judgment of the decision maker. The alternative is weighted in terms of given rating against each criterion. AHP is a hierarchical model that is used to help decision-makers to consider both objective and subjective factors while choosing the best ranking alternative. According to Satty [24], the hierarchical AHP model includes the following steps:

1. Define the problem and set the goals.
2. Choose a set of criteria/decision factors/variables.
3. Select a set of alternatives/choices.

According to an article “Decision making with the analytic hierarchy process” Satty [24] attested that the goal is the first level of the AHP, and criteria and alternatives are the second and third levels, respectively. The pairwise basis method is used to compare the alternatives. In the pairwise basis method, a ratio scale without units is used to compare alternatives. The decision-maker is not expected to make a numerical judgment. Instead, the relative value of two quantities, such as a & b, with the same intensity, meter or utility units will be the judgment. The transitivity rule could be used for all comparisons if the given matrix from the result of AHP is consistent [24].

$$a_{ij} = a_{ik}.a_{kj} \qquad \text{Eq. (1)}$$

However, this seldom would have full consistency in the AHP matrix. Webber et al. (1996) p. 78, stated that the “order in which the comparisons are entered in the matrix may affect the successive judgments”. Therefore, it is recommended to compare two criteria or decision factors at the same time instead of comparing multi criteria at the same time. Consequently, the pairwise comparison matrix (PCM) will be used to find the relative rate of different alternatives with respect to given criteria. In the PCM, the numerical scale is used to measure the qualitative decision problem. Satty [24] developed a 9-point ratio scale that transfers the verbal description of problem to numerical values. Unfortunately, the values that are used in the PCM matrix are based on the experience and expertise of the decision makers. Hence, inconsistency will result because of imperfections in the experience and expertise of the decision makers and the complexity of the problems. Furthermore, in the case of complex problems, it is very difficult to assign values to each comparison matrix. It is sometimes impossible to complete the PCM because of the complexity of the problem, time pressure and limited experience of the decision maker. However, the PCM must be completed to derive the final decision. The following definition is used in the PCM matrix [24]:

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ . & . & . & . \\ . & . & . & . \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \qquad \text{Eq. (2)}$$

- Positive reciprocal matrix: if $a_{ii} = 1$, $a_{ij} = \frac{1}{a_{ji}}$ and $a_{ij} > 0$ for all i and j is a positive integer.
- Consistence positive reciprocal matrix: if $a_{ik}a_{kj} = a_{ik}$, for all i, j, k is a positive integer.

- Approximately consistence positive reciprocal matrix: if $a_{ik}a_{kj}\approx a_{ik}$, for all i, j, k is a positive integer.
- Transitive positive reciprocal matrix: if *A>C* derived from *A>B* and *B>C*.
- Consistency test: in order for PCM to pass the consistency test, if the consistency ratio is *CR<0.1*. The consistency test includes the following four steps:

1. Calculate λ_{max}, which is the maximum eigenvalue of Matrix *A*.
2. Calculate CI, which is [24]:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad \text{Eq. (3)}$$

3. Calculate *CR*, which is the following equation and *RI* can be measured from table.

$$CR = \frac{CI}{RI} \quad \text{Eq. (4)}$$

4. Compare the CR against the value of 0.1, in which *CR*<0.1.

The CR method is the method most often used for AHP. According to Satty, 1-9 fundamental scale is used as a judgment scale in which the qualitative attribute of criteria collected from expert's experience and expertise is transferred to measurable scales. Table 4 shows the 1-9 fundamental scale of Satty. The Random Index (RI) will be chosen from Table 3 in order to calculate the CR.

Table 3: The Average Random Index [24].

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.30	1.35	1.40	1.45

The significant weights of each alternative need to be derived from the constructed pairwise comparison matrixes. Normalization of column sum, arithmetic mean of normalized columns, direct least square method, weighted least squares method and eigenvector methods are only 6 among 20 different techniques used to find the priority weights of alternatives from the comparison matrix [24].

Table 4: The Satty 9-Point Scale [24].

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocal of above nonzero	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.	

2.7 Quality Function Development

The quality function development (QFD) matrix is a technique used to bring the voice of customers into the process of designing and developing a product or service. By using this information, effective organizations align their processes to meet their customers' needs and their target goals. Companies use the customer's information, which is obtained by QFD, to make changes in their provision of services. According to Kenneth [25], the following steps should be used to create the QFD [25]:

1. The needs and requirements of the process should be stated on the left side of matrix, which is organized according to affinity diagram categories. This process of prioritization should be addressed by using a 1-5 rating scale.
2. Surveys or expert panels should be obtained to get feedback about the level of importance of each system in order to evaluate them against each other. The strength and weakness of each alternative or element should be identified in relation to the competition. This strategy is very important in determining the development efforts that have the best results.
3. The appropriate elements for each main system are identified to respond to process requirements and to organize them into related categories.

4. The relationship between each main category of the system and its subcategories should be developed. Strong, medium and weak relationships are used in this section of matrix.
5. The technical evaluation of each main category, which is considered the process index, should be conducted to develop an index to benchmark the applied performance in competitive countries. Information about applied systems should be collected based on the system requirements and technical characteristics.
6. The preliminary target value of each main category of the system should be established.
7. The potential positive and negative interactions between each subcategory of the main categories of the system should be determined by using strong and medium, positive and negative relationships.
8. A weighting factor is assigned to relationship symbols (9-3-1, 4-2-1, or 5-3-2) in order to calculate the importance rating. The importance rating is multiplied by the weighting factors in each box of the matrix, and the product results are added in each column.
9. Because of the difficulty of applying each system, a scale of 1 to 5 should be used: 5 mean very difficult and 1 means very easy. The maturity of the technology, technical qualification, business risk, accessibility of resources…etc.

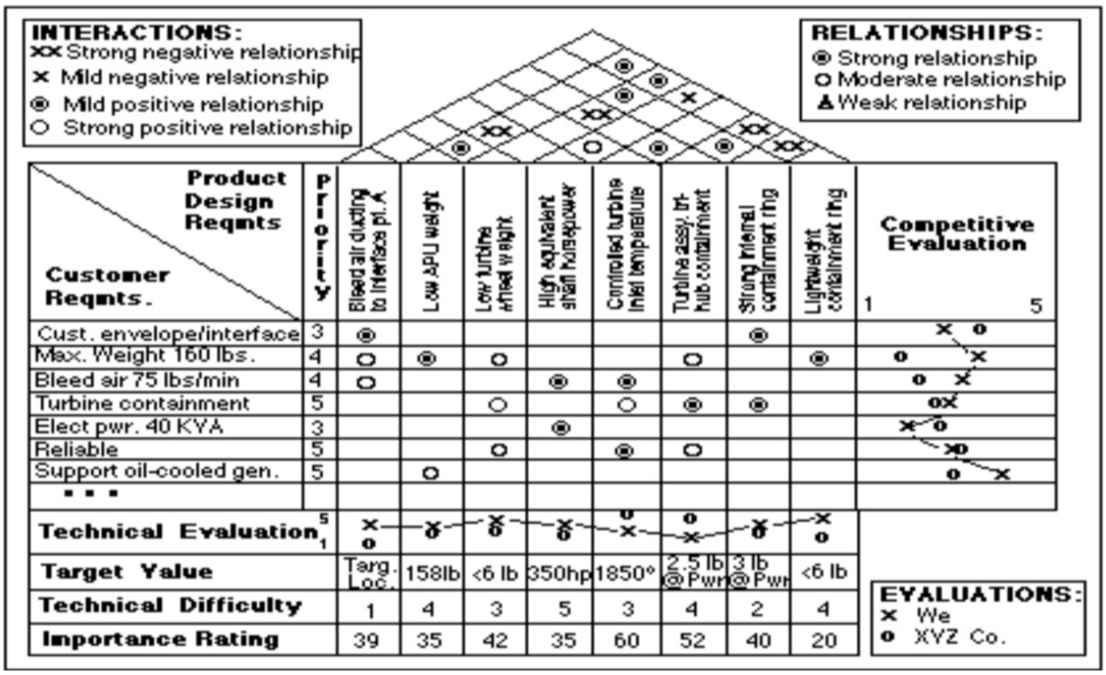


Figure 13: Quality Function Development Example [25]

Chapter 3: Methodology

This study is the first stage in the conception of a framework to benchmark the use of EMSs in metro stations. The research goal is to create and design the elements of a “Best in Class” metro station in terms of energy and cost efficiency, conservation, and management. The focus of this paper is on efficient use of energy only and the economic analysis for installation of these systems are not going to be studied in this paper. The main emphasis of these systems and the three steps, which are described below which are used to derive a metro station benchmark that can be used to plan new metro station projects and assess existing stations for retrofitting.

5. Assess the broad literature review on building and metro transit energy system techniques.
6. Design a “Best in Class” metro station benchmarking model using three categories of energy management (energy efficiency system, renewable energy system, recovery energy system). Each main category has subcategories or elements, such as LED lighting, wall insulation and platform screen doors. These are the three elements of an energy efficient system. The solar panel is the only subcategory in the renewable energy system, and energy storage is the only element in the recovery energy system.
7. Validate the design of the “Best in Class” metro station by creating an expert panel using AHP analysis and QFD matrix in the decision matrix.
8. Create an integration model (SAM) to benchmark the effectiveness of energy management practices in metro stations.

3.1 Progressive Procedure for the Design

According to Architectural drawing from the existing metro station in city of Tehran, Iran, which is shown in Appendix A, the total area of the “Best in Class” metro station is 9000 m^2. It can handle 22,000 passengers per hour, which means 11,000 passengers in both directions. The length of the platform is 170 m, which accommodates trains that are 150m long. Each train consists of six cars. The table 5 shows the designing steps needed to be followed:

Table 5: Designing Procedure for "Best in Class" Metro Station

"Best in Class" Metro station

- The following steps are necessary to follow in designing the "best in class" metro station

Objectives

- **Identify project objectives**: The project's objective will be decided according to the energy enactment, climate, cost, availability of materials, available space and other constraints.

Design

- **Design:** Decide on the best suitable LED lighting, solar panels, energy storage, platform screen doors and insulation for walls and ceilings to be installed in the "best in class" metro station. Review the required specifications needed to implement in the design.

Building

- **Review the building code of the target country**: Determine the minimum energy requirements and safety codes codes in the local location.

Construction

- **Construction:** The construction process of the "best in class" metro station should be planned with appropriate sequencing and staging.

3.1.1 “Best in Class” metro station parameters and design dimensions.

Table 6 identifies some initial information needed to design the best system for the “Best in Class” metro station.

Table 6: "Best in Class" Metro Station Dimensions

“Best in Class” metro station	Value
Finished Floor Area (m^2)	9,000
Ceiling Area (m^2)	3,055
Slab Area (m^2)	3,055
Wall Area (m^2)	2,800
Platform Screen Doors (No.)	12

3.1.2 Platform type.

The center platform and the side platform are the two main types of platforms in metro stations. Figure 14 shows the handling capacity needed to control crowds coming from both trains on the center platform. In a report entitled “Transit Capacity and Quality of Service Manual” by National Research Council [26] ,on the side platform, there are vertical transportation devices, which allow separating the traffic flows, hence improving the handling capacity of the metro station. In our metro-station design, we will use the side platform, which handles passengers easily.

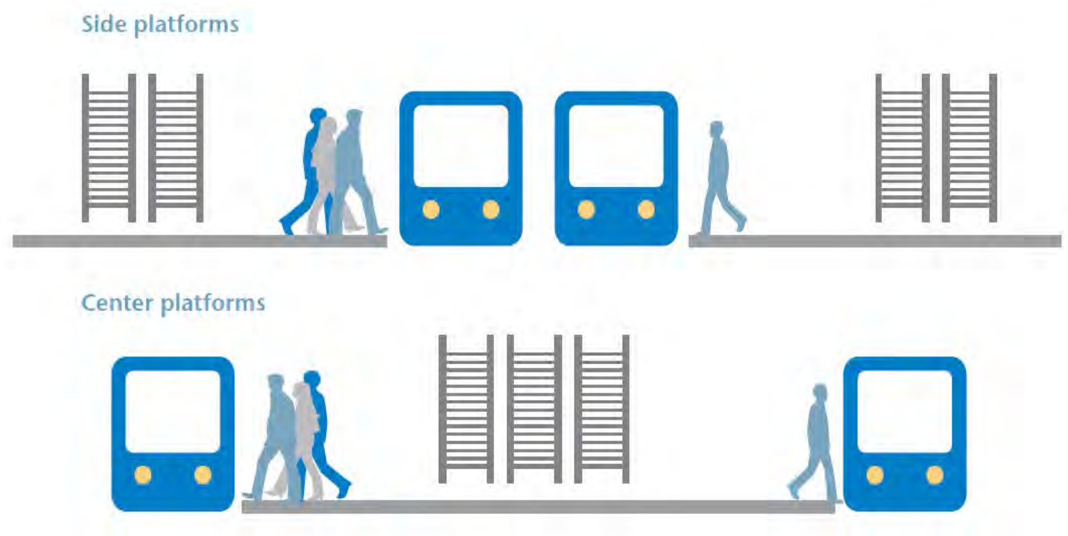


Figure 14: Side and Center Platforms [26]

3.1.3 LED lighting system.

Some principles should be adhered to in the efficient design of the lighting system in the "Best in Class" metro station:

1. The lighting system should meet the lighting-level requirements.
2. The applied lighting system should operate in at maximum efficiency usage.
3. The operation of the lighting system should be controlled automatically.

According to the above principles, some criteria were created to confirm the efficiency of using LED lighting in the "Best in Class" metro station:

- ✓ The numbers of LED lighting required in the "Best in Class" metro station.
- ✓ The output of the LED lighting system in terms of lumens and fixture Lu.
- ✓ The energy efficiency of the LED lighting system, which will be measured in terms of lumens per watt (Lu/watt).
- ✓ The color-rendering index of the LED lighting system-CRI.
- ✓ The temperature of the LED lighting system in degrees Kelvin.
- ✓ The types of sources of the LED lighting system.
- ✓ The quality of the LED lighting system selected for the metro station.

3.1.3.1 Lighting requirements.

The Illuminating Engineering Society (IES) sets the acceptable amount of lighting system in any structural building. For example, the minimum lighting requirement for schools and commercial offices is 500 Lux (light level measured by using a light meter) and 300 Lux for factory floors. The standard requirements for lighting in a common building in watt/m^2 unit are listed in ASHRAE 90.1 Commercial Building Code. A lighting system is composed of three main parts: luminaires (fixtures), ballasts and light sources (lamps) [27].

3.1.3.2 Energy efficiency.

Because the energy efficiency of a LED lighting system has no units, it will be shown as a percentage. To calculate the energy efficiency of LED lamps, the ballast (electronic devices needed for lamps to charge and run) power is added to the lamp power to compute the corrected total wattage input [27]. In order to maximize the energy efficiency of the LED lighting system, a higher lumen per watt rating is required for the lamps.

3.1.3.3 Lighting temperature.

According to a report entitled "LED lighting system in Sustainable Building Design", by BetaLED Corporation [27], the color temperature of the lamps will determine the range of light color. Lamps with low color temperature tend to have a warm tint, such as red, yellow or orange. Lamps with high color temperature tend to have cool tints, such as green, violet and blue. Lamp color temperatures range between 2,600 kelvins (incandescent) to 6,500 kelvins (daylight lamps).

3.1.3.4 Color rendering index.

In an article entitled "Energy Efficient Lighting System Design for Building" Norsyafizan [28] attested that the color-rendering index (CRI) controls the quality of lighting by determining the visibility of color under selected lamps. Actually, it varies from 0 to 100 CRI. A higher CRI means that the lamp shows the color clearly and correctly. According to the US EPA Green Lights program, CRI rates and lighting quality are as follows:

- ✓ 75-100 → Excellent lighting color
- ✓ 65-75 → Good lighting color
- ✓ 55-65 → Fair lighting color
- ✓ 0-55 → Poor lighting color

The lumen method formula is used to determine the number of lamps needed in the "Best in Class" metro station [28].

$$N = F1 \ x \ A \ / \ Lu \ x \ LLF \ x \ Cu \qquad \text{Eq. (5)}$$

- N = Number of required LED Lamps
- F1 = Lux level required at target
- A = Area of task location (m2)
- Lu = Lumen output per LED lamps
- Cu = Utilization coefficient of selected LED lamps
- LLF = Light loss factor of selected LED lamps

3.1.3.5 Worksheets for Design of LED lightings:

The minimum standard service IL luminance categories and conversion from lux to foot-candles for different areas are shown in Table 7. These are used to design the LEDs lighting system for the "Best in Class" metro station. Table 8 indicates the specifications of different types of LED lighting that will be used in the "Best in Class" metro station. The sample calculation of the LED lighting in Area 1 is given below.

Table 7: Minimum Standard Service IL luminance [29]

No	Building Part	Standard Illuminance, Lux	Illuminance category	Foot-candles
1	Entrance Hall	20-30-50	C	2-3-5
2	Rest Rooms	150	C	15
3	Corridors and stairways	150	C	15
4	Public Spaces	20-30-50	A	2-3-5

The remaining calculations for the LED lighting fixtures and lamps needed for the "Best in Class" metro station are given in Table 9.

$$N = \frac{150x2450}{1500x4x0.9x0.99} = 23\ Fixture$$

Table 8: LED Lighting Specifications

LED product Name	16 W LED	8.5 W LED	16.5 W LED
Wattage (W)	16 W	8.5	16.5
Voltage (V)	200-420	100-240	200-420
Line frequency (Hz)	50/60	50/60	50/60
Dimmable	No	No	No
Rated luminous-Flux (Lm)	2000	1100	2100
LLF (%)	100	70	100
Rated Average Life (Hours)	40000	40000	40000
Dimension (mm)	1000	600	1200
Energy consumption (kWh)	18	11	19

As Table 9 shows, the total number of fixtures for Areas 1-5 is 43. There are four lamps per fixture, which gives the total of 176 lamps for the entire metro station.

Table 9: Design of LED Lighting for the "Best in Class" Metro Station.

Part	Area (m2)	Lamp Type	Light level Lux	No of Fixture	Lamp per Fixture	Total Lamps
1	2450	LED 16 W	1500 Lm (50 Lux)	23	4	92
2	400	LED tube 16.5 W	1100 Lm (150 lux)	8	4	32
3	140	LED tube 16.5 W	1100 Lm (150 lux)	3	4	12
4	126	LED tube 600 mm 8.5W	2100 Lm (150 lux)	5	4	20
5	126	LED tube 600 mm 8.5W	2100 Lm (150 lux)	5	4	20
Total Number of Fixtures and Lamps				44	-	176

3.1.4 Solar panel systems.

In a book entitled "Solar Power in Building Design" Gevorkian [9] stated that some main criteria should be considered in designing the solar panels for the "Best in Class" metro station. These are explained below:

1- In solar panel design, shading should be avoided because of its oppositional effect on solar technologies. If PV panels are exposed to shading, that portion of the solar cells can no longer function properly and will not be able to collect energy from sunlight.
2- The zoning laws of the country should be checked before making decisions about designing the solar panels in the "Best in Class" metro station.
3- The best place for the installation of the solar panels in the metro station should be selected. It is expected that the best place will be the roof area.
4- The south-facing location of the sloped rooftop should be selected for the installation of the solar panels because the energy collection will be optimized.
5- The standing seam roof is the best option for installing the solar panels in the "Best in Class" metro station because they can be easily attached without penetrating the roof.
6- The roof of the "Best in Class" metro station should be designed to carry the dead and live loads of the PV panels and the ST system. The following are examples of solar panel systems with different live loads and dead loads:

- Unglazed Solar Pool Heater-2.5 lb/ft^2 of collector area.
- Glazed Flat plate collector-5.5 Ib/ft^2 of collector area.
- Evacuated Tube collector-5.5 ib/ft^2 of collector area.

If the PV system is used in the “Best in Class” metro station, the dead load and the live load of the PV system will be 3 Ib/ft2 per collector area. In Figure 15, the blue arrows show the live load, and the red arrows show the dead load.

7- Dynamic loads, such as wind load, also should be calculated in designing the roof of the metro station.
8- Flashed stand off and proper sealing should be used for roof penetration in order to avoid leakage.
9- The electrical panels, which are connected to the PV system, need to be in a convenient location, and they should be large enough to handle both PV energy and grid energy. The total energy of the “Best in Class” metro station should not exceed 120% of the panel rating.

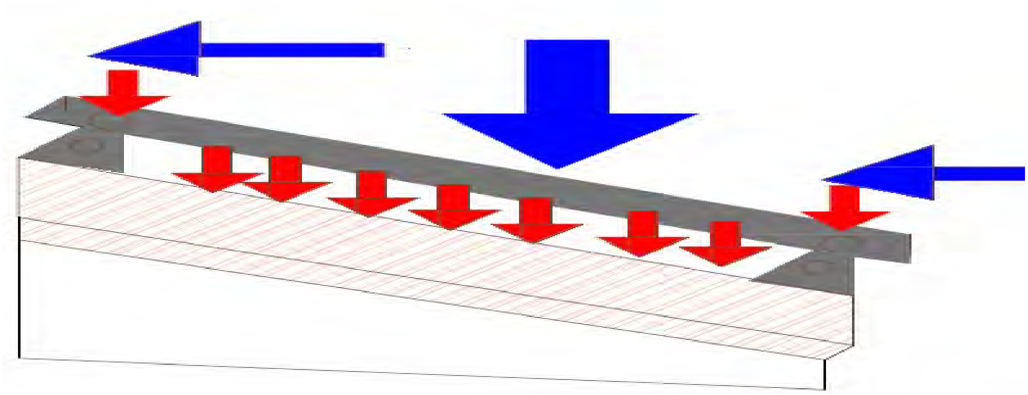


Figure 15: Dead Load and Live Load on PV panel

3.1.4.1 PV system design.

The grid-connected PV system will be used for the “Best in Class” metro station. This PV system does not require batteries because the grid collects energy from the PV generator according to the National Electrical Code (NEC) [9].

3.1.4.2 Determining the operational time for total current load.

First, the nominal operational voltage of the PV system is identified from the solar sheets, which are available on the market. In terms of the DC load, the total energy required per day by the metro station is measured by individual power rating appliance [W] times the daily operational time. In the case of the AC load, which is our concern, the required energy has to be expressed as a DC load because the PV modules will generate energy in DC electricity [30]. The PV panels will be used to generate the electricity to cover the energy required by the LED lighting system of the “Best in Class” metro station [30].

1. The total energy is required for LED lighting system:

$Wattage\ per\ lamps\ x\ (Number\ of\ Lamps)$ Eq. (6)

- For Area [1]: $16(\mathrm{W}) * (92\mathrm{N}) = 1{,}466.5\mathrm{W}$
- For Area [2-3]: 16.5(W) * 44(N) = 726 W
- For Area [4-5]: $8.5(\mathrm{W})\mathrm{x}40(\mathrm{N}) = 340\mathrm{W}$
- Total [1-5]: 1466+726+340 = 2,532 W

2. The daily requirement of energy for the LED lighting system in the “Best in Class” metro station is calculated as follows [30]:

a) DC requirement (Wh/day):

$(Total\ Wattage)\ x\ (hour/day)$ Eq. (7)

- DC for Area [1-5] 2,534W*10(hour/day) = 25,340 Wh/day

b) AC requirement (Wh/day):

(Wh/day)$x(DC\ requirement)/$ (0.85) Eq. (8)

- AC for Area [1-5] 1568/0.85 = 29,513 Wh/day

3. Ampere-hour (Ah) [30]:

$Total\ AC\ requirements\ /Voltage\ of\ system$ Eq. (9)

- Total Ampere-hour: (29,513)/24=1,230 Ah

Considering the system losses in PV system design measurement: Energy losses in the components of the PV system should be considered in determining the energy requirement. For instance, 20% will be added to cover these losses [30].

4. Ampere-hour system losses: 1,230 x 1.2 = 1,476 Ah

Determining the solar radiation of the location in which the “Best in Class” metro station will be constructed will be based on several factors, such as weather conditions and climate change. The installation of the solar panel system will affect the PV system’s energy collection. Therefore, it is very important to know whether the PV system is used all year round or only during a certain period. The solar radiation data on a particular location should be identified. For example, if the “Best in Class” metro station is located in the Netherlands (worst case scenario in terms of low solar radiation), the average solar radiation will be as follows [30]:

5. Average solar Radiation:

$$1000\ kWh/m2\ /\ 1\ kW/m2 = 1000\ equivalent\ sun\ hour\ Average \qquad \text{Eq. (10)}$$

- Solar radiation/day: 1000 hour/365 day =2.8 day

6. Total array current:

$$Ampere - hour\ (Ah)/\ (Solar\ radiation\ (/day)) \qquad \text{Eq. (11)}$$

- Total array current of the system: 1,476 Ah/3 day = 490 Ah

Determining the optimum number of modules for the PV system: the total current for an array solar system with a minimum number of modules will give the optimum arrangement of modules for the “Best in Class” metro station. There are two arrangements: parallel and series. In the parallel arrangement, the PV system current will increase, whereas in the series arrangement, the nominal voltage of the PV system will increase. To calculate the number of models in the parallel arrangement, we use the following equation [30]:

7. Number of models in the parallel arrangement:

$$\text{T}otal\ current\ required\ from\ solar\ arrays/\ current\ generated\ by\ modules\ at\ peak\ power \qquad \text{Eq. (12)}$$

To calculate the number of models in the series arrangement, we use the following equation:

8. Number of models in the series arrangement:

$$Nominal\ PV\ system\ voltage\ /\ Nominal\ module\ voltage \qquad \text{Eq. (13)}$$

Alternative 1: Diamond CS6 K-260-PG modules will be used. The following specifications show the nominal voltage and currents generated by the modules. As Table 10 shows, the optimum current of modules is 8.56 A, and the total required current generated by solar arrays, as calculated per Equation (12), is 490A. The number of parallel modules needed in the PV system is measured as follows:

- No of modules in Parallel: 490/8.56=57 No
- Total weight of Modules: 57 kg*20= 1,140 Kg

Table 10: Electrical and Mechanical Specifications for the PV Panels [31]

ELECTRICAL DATA / STC

Electrical Data CS6K	260P-PG
Nominal Max. Power (Pmax)	260 W
Opt. Operating Voltage (Vmp)	30.4 V
Opt. Operating Current (Imp)	8.56 A
Open Circuit Voltage (Voc)	37.5 V
Short Circuit Current (Isc)	9.12 A
Operating Temperature	85' c
Max. System Voltage	1500 V (IEC)/1000 V (UL)
Module Fire Rating	Type 3
Max. Series Fuse Rating	15 A
Power Tolerance	0 ~ + 5 W

Under Standard Test Conditions (STC) of irradiance of 1000 W/m2, spectrum AM 1.5 and cell temperature of 25 °C

MODULE / MECHANICAL DATA

Cell Type	Poly-crystalline, 6 inch
Cell Arrangement	60 (6x10)
Dimensions	(1650x992x27.3 mm)
Weight	23 kg
Cable	4 mm^2 (IEC) 12 AWG

Alternative 2: The LG MONO X NEON 300 W solar panel will be used for the “Best in Class” metro station. The following specifications show the nominal voltage and currents generated by the modules. In table 11, the optimum current of the modules is 9.42 A, and the total required current generated by the solar arrays, as calculated by Equation (21), is 171 Ah. The number of parallel modules needed in the PV system is measured as follows:

- No of modules in Parallel: 490/9.42=52 No
- Total weight of Modules: 52 kg*18.12=942 Kg

Table 11: Electrical and Mechanical Specifications for the PV panels [31]

ELECTRICAL DATA / STC

Electrical Data LG MONO	X Neon 300 W
Nominal Max. Power (Pmax)	300 W
Opt. Operating Voltage (Vmp)	32 V
Opt. Operating Current (Imp)	9.42 A
Open Circuit Voltage (Voc)	39.5 V
Short Circuit Current (Isc)	10 A
Operating Temperature	-40 to +90
Max. System Voltage	600(UL), 1000(IEC)
Module Fire Rating	Type 3
Max. Series Fuse Rating	15 A
Power Tolerance	0 ~ + 5 W

Under Standard Test Conditions (STC) of irradiance of 1000 W/m2, spectrum AM 1.5 and cell temperature of 25 °C

MODULE / MECHANICAL DATA

Cell Type	Mon crystalline
Cell Arrangement	60(6x10)
Dimensions	156x156 mm^2
Weight	18.12 Kg
Cable	2x1000 mm (IEC) 12 AWG

Alternative 3: The ZS- M-145 solar panel will be used for the "Best in Class" metro station. The following specifications show the nominal voltage and currents generated by the modules: As shown in Table 12, the optimum current of modules is 8.5 A, and the total required current generated by the solar arrays, as calculated by Equation (21), is 1474 A. The number of parallel modules needed in the PV system is measured as follows:

- No of modules in Parallel: 490/8.5=57 No
- Total weight of Modules: 11.8 kg*57 = 673 Kg

Table 12: Electrical and Mechanical Specifications for the PV Panels [31]

ELECTRICAL DATA / STC

Electrical Data	ZS- M-145
Nominal Max. Power (Pmax)	140 W
Opt. Operating Voltage (Vmp)	21.8 V
Opt. Operating Current (Imp)	8.5 A
Open Circuit Voltage (Voc)	39.5 V
Short Circuit Current (Isc)	8.748 V
Operating Temperature	-40 to +90
Max. System Voltage	1000 V DC
Module Fire Rating	Type 3
Max. Series Fuse Rating	15 A
Power Tolerance	0 ~ + 5 W

Under Standard Test Conditions (STC) of irradiance of 1000 W/m2, spectrum AM 1.5 and cell temperature of 25 °C

MODULE / MECHANICAL DATA

Cell Type	Mon crystalline
Cell Arrangement	60(6x10)
Dimensions	1482x670x36 mm
Weight	11.8 Kg
Cable	2x1000 mm (IEC) 12 AWG

According to the above calculations, the best PV panel for the “Best in Class” metro station roofing area is ZS-M-145, which has a lower dead load with 673 kg.

3.1.5 Flywheel energy storages.

Some key factors in the design of flywheel energy storage, that is, the amount of energy storage in flywheels and the specific energy of flywheels, are listed below:

1- Materials
2- Geometry
3- Length
4- Bearings

3.1.5.1 Materials.

According to Haichang and Jiang [18], steel and carbon fiber or graphite are the two main materials used to make flywheels. Carbon fiber flywheels have high strength, are lightweight and have high specific energy. On the other hand, steel flywheels have lower power and energy densities, and lower strength compared to their very heavy weight and their large diameter and slow rotation. To calculate the amount of energy stored in a flywheel, the following formula is used [18]:

$$E = \frac{1}{2} I\omega^2 \qquad \text{Eq. (14)}$$

- I = moment of inertia (Kgm^2) (ability of an object to resist changes in its rotational changes)
- ω = Angular velocity (Rad/sec)

$$I = kMr^2 \qquad \text{Eq. (15)}$$

- k=Inertial constant (For solid disk=1/2)
- M= Mass of flywheel (kg)
- r= Radius (m)

The tensile strength of the flywheel will determine the maximum energy that can be stored in it. The maximum specific energy can be stored in the flywheels' energy storage [18]:

$$E_{sp} = K_s \, \sigma_m/\rho \qquad \text{Eq. (16)}$$

- E_{sp} = Maximum specific energy (Wh/kg)
- K_s = Shape factor
- σ_m = Maximum tensile strength (GPa)
- ρ = Density of flywheel (kg/m^3)

As shown in Table 13, the choice of material heavily depends on high tensile strength with low density. Both T-700 and T-1000, which are fiber composite materials, have the highest tensile strength with the lowest density. Therefore, the best material to use for flywheel energy storage in the "Best in Class" metro station is the fiber composite.

Table 13: Physical Properties of Different Types of Flywheel [18]

Rotor materials	σm (GPa)	ρ (Kg/m3)	E_{sp} (Wh/kg)
E -glass	3.5	2540	190
S-glass	4.8	2520	265
Kevlar	3.8	1450	370
Spectra 1000	3	970	430
T-700 graphite	7	1780	545
T-1000 graphite	10	-	780
Managing steel	2.7	8000	47

3.1.5.2 Geometry.

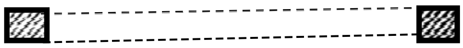
In order to maximize the specific energy, the proper geometry of the flywheel should be chosen. The first step is to adjust the flywheel’s moment of inertia by increasing the density. The axis of rotation should be as far as possible from the mass of the flywheel [18]. Table 14 shows the various Ks factors that can be used to optimize the shape of flywheels. The shape factor of the flywheel energy storage will determine the efficiency of the rotor shape. The rotor shape is not the only factor that influences the maximum stress of composite rotor. Other factors include loading condition, materials and failure modes.

According to Haichang and Jiang [18], the hollow cylinder is the best shape to maximize the specific energy in flywheel energy storage. Therefore, hollow cylinder shape will be used for flywheel energy storage in the “Best in Class” metro station.

3.1.5.3 Length.

The length of the flywheel also affects the maximization of the energy efficiency. The length of the diameter of the rotor should be such that it does not excite the conical rigid body mode in the event of the machine cycle. For that reason, the rate should be less than or larger than 1:1. In other words, whenever the rotor is running at the speed of its maximum stress, the length should be chosen as the maximum safe length under the speed of the rotor [18].

Table 14: Shape Factors for Flywheel Geometry [18]

Flywheel	Cross sectional	(Ks)
Flat unpierced disc		0.61
Thin rim		0.5
Rim with web		0.4
Flat pierced disc		0.31

3.1.5.4 Bearings.

Haichang and Jiang [18] also showed that the bearings control the spinning of the rotor. There are three types of bearings: ball bearings, magnetic bearings and high temperature superconducting (HTS) bearings. The advantages and disadvantages of each are explained below.

3.1.5.5 Ball bearings and magnetic bearings.

The main advantages of using ball bearings and magnetic bearings are their low cost, low loss, simplicity and compactness [18]. In addition, the ability to control high spin speed, isolating rotor and stiffness also make them desirable for use in energy storage. A main feature that makes ball bearings more interesting is the material composition, such as ceramic and hard steel. On the other hand, the lubricant life of magnetic bearings is much longer than that of ball bearings because of their upper bound on the spin speed.

3.1.5.6 High temperature superconducting bearings (HTC).

Recently, HTC bearings have been used in flywheel energy storage because they significantly reduce power losses by 10-50 W [18]. Because of their low frictional coefficient, they are more economical, than ball bearings and magnetic bearings are.

The only drawback of this system is the long-term development constraint. Therefore, in the “Best in Class” metro station, HTC bearings will be used in flywheel energy storage because of their very low power loss and high force in collecting kinetic energy.

3.1.6 Insulation for exterior walls.

The optimum insulation thickness for the exterior walls of the “Best in Class” metro station should be in line with both energy consumption costs and the total budget for the supply and installation of the insulation material. The optimum insulation thickness with respect to energy saving should be chosen by considering the cooling and heating loads in the “Best in Class” metro station. The insulation materials for walls will be polystyrene and rock wool. By applying this type of insulation, the energy saved by external wall areas in the “Best in Class” metro station would be almost 12% $/m^2.

3.1.6.1 Assumptions.

If the “Best in Class” Metro station is placed in a country with an external medium temperature of $t_e \leq 15$ ℃, and the internal medium temperature is be $t_h = 20$ ℃, the number of degree days would be 2,055. The external walls of the “Best in Class” metro station are made of inner plaster 200 mm thick, two horizontal bricks, rockwool and polystyrene insulation 850 mm thick, and external plaster 300 mm thick.

3.1.6.2 Insulation thickness design.

1) The first step is to calculate the annual heat loss in the external walls of the metro station using the following formulas [32]:

$$q_A = 86{,}400\, DD\, U \qquad \text{Eq. (17)}$$

- q_A= Annual heat of surface area A
- DD =Degree-days
- U =Heat transfer coefficient

2) The second step is to calculate the annual energy requirement using the following equation:

$$E_A = 86{,}400 . DD . U / \eta \qquad \text{Eq. (18)}$$

- E_A = Annual energy requirement of surface area A
- η = System efficiency

3) The third step is to find the heat transfer coefficient using the following equation [32]:

$$U = 1/(R_i + R_w + R_{ins} + R_o) \quad \text{Eq. (19)}$$

- R_i = Inner air-film thermal resistance
- R_o = Outer air-film thermal resistance
- R_w = Total wall resistance without thermal insulation
- R_{ins} = Total thermal insulation resistance for layer

4) The total thermal insulation resistance can be calculated using the following equation [32]:

$$R_{ins} = \frac{X}{K} \quad \text{Eq. (20)}$$

- x = Insulation thickness
- k = Thermal conductivity

5) In order to simplify the heat transfer coefficient equation, R_{wt} will be used:

$$R_{wt} = R_i + R_w + R_o \quad \text{Eq. (21)}$$

6) The next step is to find the annual energy requirement with respect to Equations (18) and (19):

$$E_A = \frac{86{,}400.DD.C_f}{(R_{wt}+\frac{x}{k})H_u\eta} \quad \text{Eq. (22)}$$

- C_f = Fuel cost in $/kg
- H_u = Heating in J/kg

7) The next step is to find out the insulation cost using the following equation [32]:

$$C_{ins} = C_i.x \quad \text{Eq. (23)}$$

- C_{ins} = Insulation cost in $/m^2$
- C_i = Insulation material cost
- x =Insulation thickness

8) In order to determine whether the optimum insulation was chosen for the “Best in Class” metro station with respect to both energy and cost saving, a life cycle cost analysis must be performed. Therefore, the next step is to determine the present-worth factor (PWF) by using the following formula:

$PWF = \frac{(1+r)^N - 1}{r.(1+r)^N}$ Eq. (24)

- $r = \frac{i-g}{1+g}$
- i = Interest rate
- g = Inflation rate
- N = Lifetime assumed to be 10 years

9) If inflation rate and interest rate are considered equal, the present-worth factor can be calculated using the following equation if $i = g$ [32]:

$PWF = \frac{N}{1+i}$ Eq. (25)

10) The last step is to calculate the total heating cost of the insulated walls using the following equation:

$C_t = C_A.PWF + C_i.x$ Eq. (26)

11) Finally, the following equation gives the optimum insulation thickness for the "Best in Class" metro station according to the present-worth factor, properties of insulation material and walls, corresponding price of insulation, and degree-days of the target location [32].

$x_{optimum} = 293.94 * (\frac{DD.C_f.PWF.k}{H_u.C_i.\eta}) - k.R_{wt}$ Eq. (27)

Table 15, shows the properties of the insulation materials, fuel price, degree-days of the location, system efficiency and the insulation cost of materials.

- $x_{op} = 293.94(2055 * 0.06*0.032*9.090/3.6*10^6 *29*0.99)$ ^ (1/2)-(0.032*0.592)=0.154 m
- $x_{op} = 293.94(2055 *$0.06*0.042*9.090/3.6*10^6*107*0.99) ^ (1/2)-(0.032*0.592) = 0.078 m

The two optimal thicknesses of the polystyrene and rockwool insulations are 78 and 154 millimeters, respectively, in terms of cost efficiency.

Table 15: Parameters Used to Calculate the Insulation Thickness

Parameters	Units	Values
Degree Days (DD)	℃	2055
Fuel: Electricity		
Heating Value (H_u)	J/kWh	$3.6x10^6$
Efficiency of space- heating system (η)	-	0.99
Energy cost of electricity (C_f)	$/kWh	0.06
Insulation: polystyrene		
Thermal conductivity of insulation materials (k)	(W/mK)	0.032
Insulation material cost (Ci)	$\$/m^3$	29
Insulation: Rock wool		
Thermal conductivity of insulation materials (k)	(W/mK)	0.042
Insulation material cost (Ci)	$\$/m^3$	107
Common parameters		
Sum of inside and outside air-film resistance (Ri and Ro), and total thermal resistance of wall layer without insulation (Rw); Rwt	m^2K/W	0.592
Interest Rate (i)		10%
Inflation Rate (g)		10%
Number of years (N)	N	10
Present-worth factor (PWF)		9.090

3.1.7 Platform screen doors.

The “Best in Class” metro station has two platforms with 12 sets of bi-parting doors, supporting six cars with two doors each.

3.2 Analytic Hierarchy Model

This study uses the analytic hierarchy (AHP) model of energy management in the “Best in Class” metro station. The model is used to find the proper weighting of each element: LED lighting, solar panels and so on. In the initial stage of this process, the criteria are compared using the pair wise comparison. The level of importance will be determined based on industrial requirements, as well as the experts’ judgment according to their experiences.

The study focuses only on the planning phase of the energy management process in metro station. Accordingly, the energy management process hierarchy (Figure 16) is divided into three main categories: energy efficiency systems, renewable energy systems and recovery energy systems. Each element of the "Best in Class" metro station will be a subcategory of the main categories. For instance, LED lighting, wall insulation and platform screen doors will be three subcategories of the energy efficiency system, solar panels is the subcategory of the renewable energy system and energy storage is the subcategory of the recovery energy system.

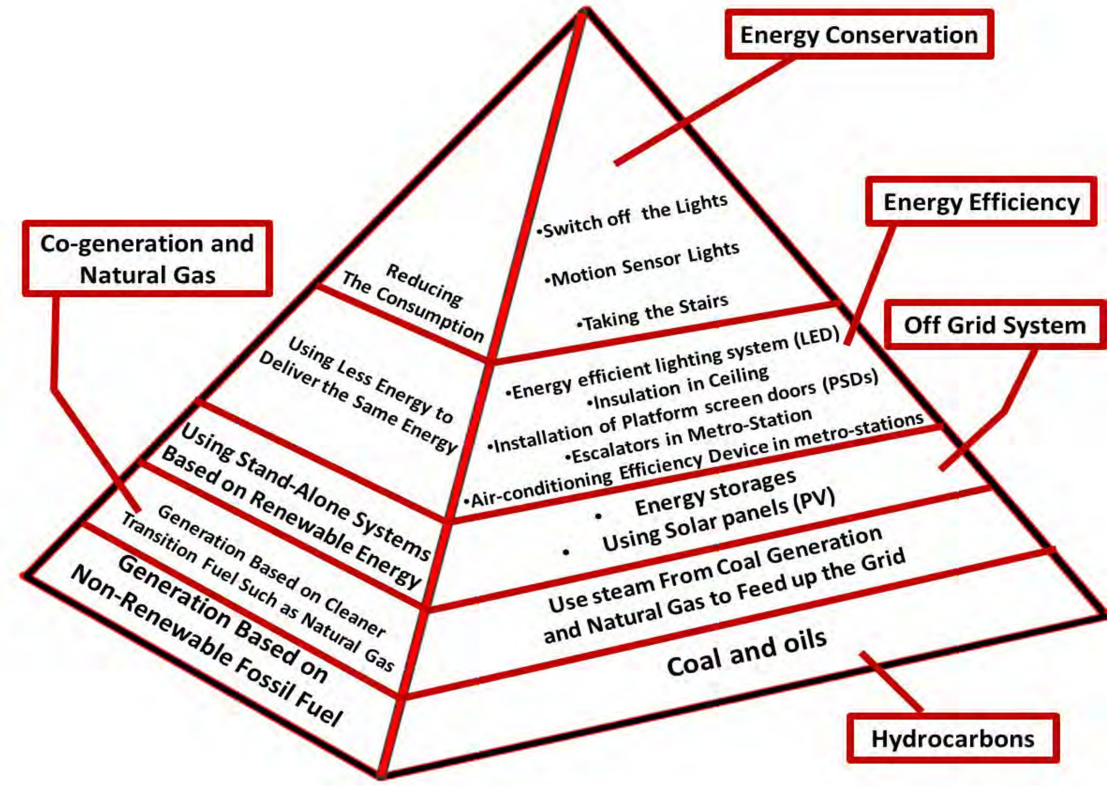


Figure 16: Modified Energy Management System

The three main categories in the "Best in Class" metro station will be compared to three main specific criteria, which are productivity, installation cost and the environmental compatibility of the systems. Productivity of system is important because of utilization factor. Utilization Factor determines the energy saving and usage capacity in these energy management systems. Consequently, installation cost of theses system is a key factor in term of economic efficiency. Finally, environmental compatibility of energy management systems has very great impact on selection of the systems in order to make sure whether these systems would not have bad effects on the health of our environment.

In the AHP model, the comparison of both criteria with respect to each other or, with respect to the three main categories of the energy management system, will be weighted using the 1-9 rating scale shown in Table 4. For instance, the rate (1) will be used if a criterion or one of the main categories is compared to itself. Next, if one criterion or main category (X), which is compared to other main category or criterion Y, has the weight of 5, in return the criterion or main category Y with respect to X has the weight of 1/5. The main categories of energy management and the criteria will be evaluated using subsequent mathematical operations. The first step of this operation is to find the inconsistent matrix total weight of each column in each process. For instance, in the energy efficiency system, the column sum would be = W1+W2+W3 (W = process's weighting), so the energy efficiency system column = 1+1/8+1/7 = 1.268. Subsequently, to normalize the matrix, each column entity will be divided by conforming the sum of the columns. Therefore, the column entity for this example is l 1, 1/8 and 1/7 in which each is divided by 1.268, which gives rates of 0.79, 0.098 and 0.11. Their total will be equal to 1. Consequently, the same steps will be conducted for the row entities.

Consequently, in order to normalize the rows and find the overall priority process, the total rates of each row are determined, and each row entity will be divided by the sum of the rows' entities. In this example, the sum of the energy efficiency rows is (5/7+4/7+3/4)/3 = 0.67. Then, the consistency vector then will be measured by multiplying inconsistency matrix entity of each column by its corresponding overall priority process. In our example, Energy efficiency column = 1*0.67+8*0.067+7*0.244=2.914. The priority vector will then be multiplied by all its inconsistence matrix rows (2.94/0.67=4.38, 0.3015/0.067=4.5, 1.1/0.244=4.51). The next step is to find the consistence vector ($\lambda_{max} = Avrage\ of\ all\ cosistance\ vector$) and the consistency index (CI=$\lambda_{max} - n\ (n - 1)$ where n is the number of matrix entities) and the consistency ratio (CR = CI/Random inconsistency). The following shows the calculation for λ_{max}, CI and CR used in this study:

- $\lambda_{max} = \frac{4.38+4.5+4.51}{3} = 4.46$
- $CI = 4.46 - 3\ (\frac{3}{2}) = 0.04$
- $CR = {}^{0.04}/_{0.52} = 0.076\ CR < 0.1\ ok$

Finally, the final process ranking is calculated by multiplying the priorities of the main categories by the priority of all criteria. The sum of the final process ranking is calculated to determine the vectors of all priorities.

3.3 Expert Questioners

Six professional questioners comprise the AHP expert panel. Three were from the field and three were from the academia. Appendix B shows the input of the expert panel regarding their opinions about the energy management systems used in metro stations, which includes three main criteria (system productivity, installation cost and environmental compatibility) and three main categories (energy efficiency elements, renewable energy elements and recovery energy elements). They were required to use a pair-wise comparison to state their opinions about the best practical category of metro stations with regard to best energy performance. The consistency and stability of the experts' judgments will be evaluated by using a sensitivity analysis.

3.4 Energy Management Elements Index

The outcome of the AHP will help to develop the decision matrix using the quality function development (QFD), which leads to the best practices in energy management in metro stations. This will assist both governments and private sectors to evaluate the level of integration into the energy management performance in metro stations. This prioritization of the integrated process will be used to weight the decision matrix in the QFD analysis. The QFD matrix will help parties to identify the appropriate subcategories of energy management, such as LED lightings, solar panels, flywheel energy storages and so on.

3.5 QFD Decision Matrix

In this step, the rating process index and the AHP driven prioritization will be used to create the QFD decision matrix. In addition, the QFD can be used as an index to compare the level of energy efficiency in metro stations of different countries. The following steps will be used in creating the decision matrix in QFD:

1. Determine the main categories in energy management: This step was already identified in the AHP process. The three main categories in energy management in metro stations are the energy efficiency system, renewable energy system and recovery energy system. LED lighting, platform screen doors and wall insulations are the three subcategories of the energy efficiency system; the solar panels and geothermal heat pumps are the

subcategories of the renewable energy system; and energy storage is the subcategory of the recovery energy system.

2. Rank the importance of each subcategory according to the prioritization of the main categories determined by AHP. A ranking from 1 to 10 should be used where 10 means extremely important and 0 means not applicable.
3. Evaluate the target or reference model (i.e., the metro station) against other metro stations in different countries.
4. Determine the direction of improvement for the technical requirements. For instance, after the analysis of the level of energy management in the metro stations in each country, the efficiency weaknesses and strengths will be determined, and the direction of improvement for better energy efficiency will be identified.
5. In this step, the relationship between the main categories in energy system management and their subcategories will be determined according to the following correlations.

- A strong positive correlation is denoted by value of 9 or a filled-in circle.
- A positive correlation is denoted by value of 3 or an empty circle.
- A weak correlation is denoted by a value of 1 or a triangle.

6. Determine the correlation between subcategories.

- A positive correlation is denoted by an open circle.
- A negative correlation is denoted by an x.
- No correlation is denoted by an empty option.
- A negative correlation is denoted by a minus sign.

7. Determine the column weights. The correlation values for the “wants and hows” are multiplied by the value of expectation ranking.

Chapter 4: Analysis

This chapter will focus on the expert judgments about the energy management in metro stations based on the results of the analysis of AHP priorities. The first part of this chapter stipulates the process ranking in which the concluding outcome will be used in QFD matrix. The decision-making software Expert Choice will be used to evaluate the AHP analysis by using the experts' judgments. In this software, the target goal is to choose the best energy management system in metro stations. Three criteria are specified in a hierarchical system (Figure 17): system productivity, initial cost and environmental compatibility. Three alternatives are given: an energy efficiency system, renewable energy system and recovery energy system. The inconsistency ratio for each pair-wise comparison between the criteria and the alternatives with respect to the criteria will be calculated, and they should be less than 0.1. The overall vector will be calculated for the planning phase of the energy management process. Six expert questioners were used in this study. In this software, the combined judgment of all experts is used as the final judgment. In order to combine the judgments of all experts in order to weight the criteria and alternative priorities, a geometric mean has to be used, which is shown in the following formula [24]:

$(i = \prod_{1}^{n})^{(1/n)} = \sqrt[n]{(a_1 a_2 \ldots a_n)}$

a = expert input

n = input number

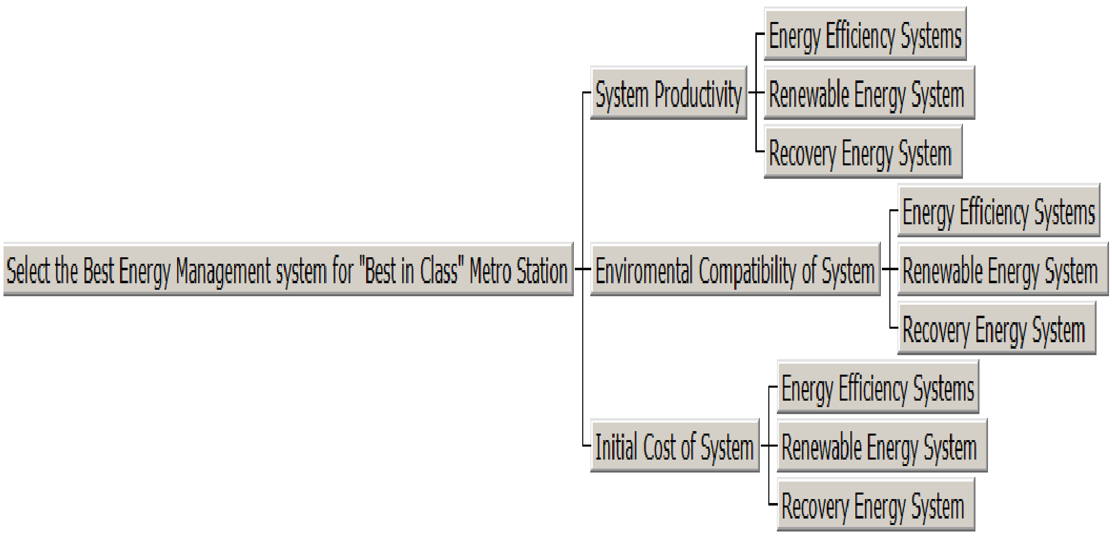


Figure 17: Hierarchy of Energy Management

4.1 Criteria and Alternative Ranking of Expert Panels

The data on the expert judgments is updated by using the pair-wise comparison in expert choice. The results showed that 50.2 % of experts prioritized the criterion of system productivity over the other two criteria: initial cost and environmental compatibility of system. The second criterion prioritized was the initial cost of applying the system, which was 34.7%. Figure 18 shows the results of the criteria ranking analysis of the energy management process using the Expert Choice software. The last priority ranking is for the environmental compatibility of the system. The results showed a slight inconsistency of around 0.00845, which is very small and can be neglected.

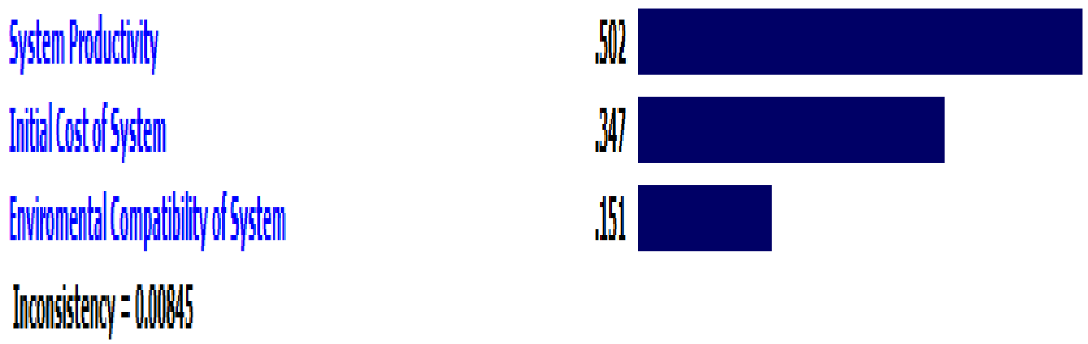


Figure 18: Priority Ranking of Criteria

4.2 Priorities of the Elements of the Energy Management System

Five elements are considered in the energy management of the metro station. LED lighting, wall insulation and platform screen doors are the subcategories of the main categories of the energy efficiency system. Solar panels are the subcategory of renewable energy system. Energy storage is the only subcategory of the main category of the recovery energy system. Figure 19 shows the combined instance synthesis of three main categories with respect to the goal. The results showed that 61.2% of the experts ranked the energy efficiency system as the highest priority with respect to other three criteria. The second highest priority was the renewable energy system with a rank of 20.7%. The third highest was energy storage with a rank of 18.1%. Both field and academic experts gave the highest priority to the energy efficiency system in metro stations, which includes LED lightings, wall insulations and platform screen doors. The overall inconsistency for the combined priorities of the main categories of energy management was 0.

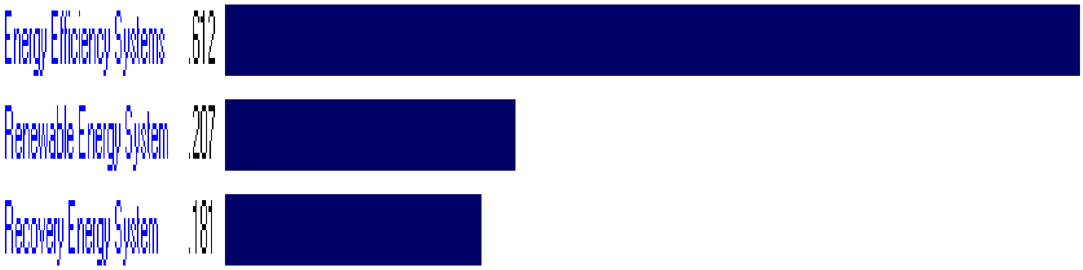


Figure 19: Priorities of the Main Categories of Energy Management

4.3 Sensitivity Analysis

The last step in the AHP analysis using the Expert Choice software is the sensitivity analysis in which the input was altered to determine the effect on the results. The sensitivity analysis was used to ensure the consistency and the accuracy of the results. For instance, if the ranking of the main categories did change, even if we changed the percentages of the criteria priorities or vice versa, the results would be robust. Figure 20 presents four different graphical representations of the sensitivity analysis: head to head, dynamic, performance and 2D.

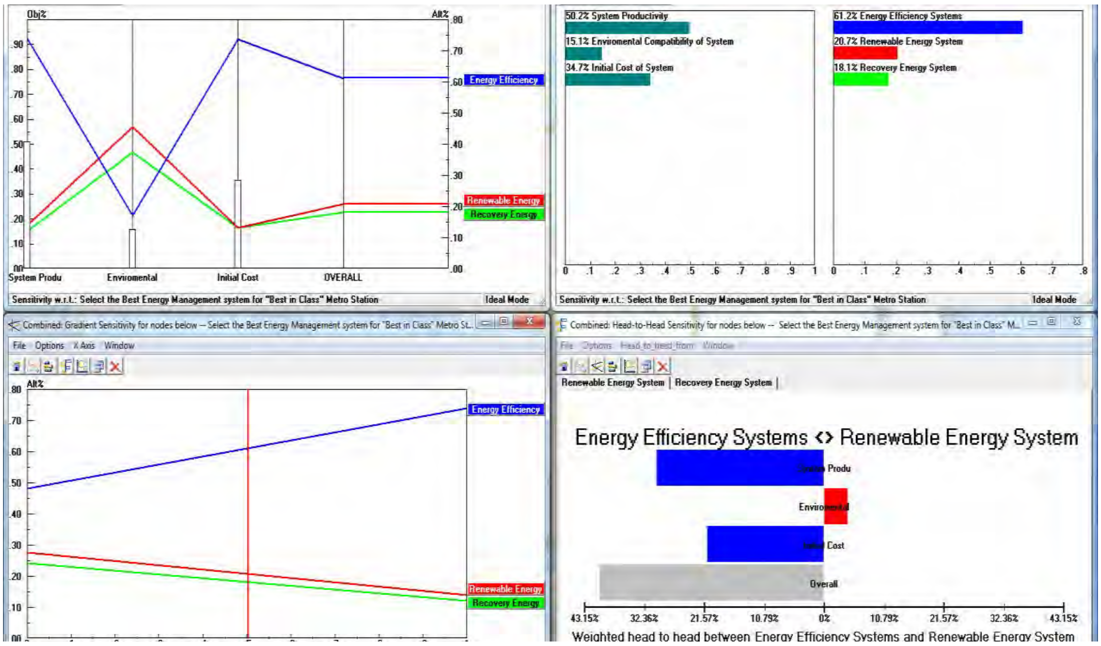


Figure 20: Four Graphical Representations of the Sensitivity Analysis

The dynamic sensitivity analysis is used in this study. Figure 21 shows the results of the dynamic sensitivity analysis before any changes in the ranking of criteria or main categories.

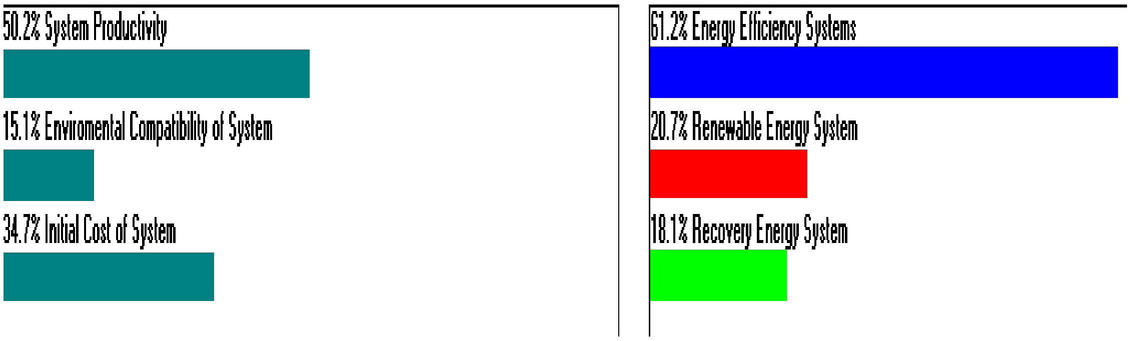


Figure 21: Main Categories Priority before Sensitivity Analysis

For instance, if the environmental compatibility ranking increased by 10%, the energy efficiency system would remain the same as the highest priority in the system by 45.2%. In other words, we could say that our results are robust, and even if we changed the ranking of criteria, the results would remain the same. Figure 22 shows the sensitivity analysis after the changes were made in the ranking of environmental compatibility.

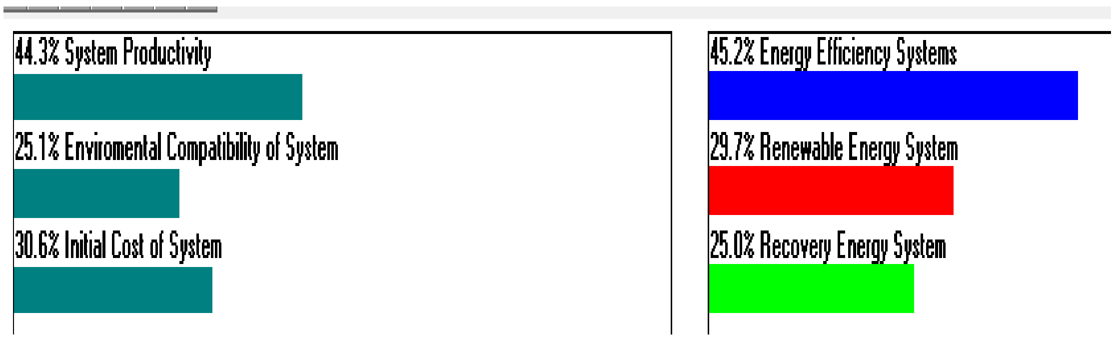


Figure 22: Sensitivity Analysis after Changes in Environmental Compatibility

4.4 Quality Function Development Analysis

Now, we would calculate the relative importance of the elements in the energy management of the “Best in Class” metro station according to the AHP analysis. The level of difficulty can be extracted from the initial cost priorities according to the experts’ judgment. The initial cost priority was 34.7% in criteria ranking. It was used as the basis of the level of difficulty where if the initial cost of the system is high, the level of difficulty is also high. The energy efficiency system was determined to have the least initial cost by almost 67% of expert judgments. The level of difficulty of energy efficiency was 4. Both the renewable and recovery energy systems had the same priorities for initial cost. The level of difficulty of both was 8. The direction of improvement of the energy efficiency system, which includes the elements of LED lighting, wall insulation and platform screen doors was x, which means that the objective has to hit the target. The direction of improvement was Δ in the renewable and recovery energy systems, which includes solar panels and energy storage. This result indicates that the objective was maximized.

The relationships between the main categories and their subcategories were also defined. There was a strong relationship between the energy efficiency system and the elements of LED lighting, wall insulation and platform screen doors. Solar panels and energy storage had a weak correlation with the category of the energy efficiency system. Solar panels had a strong relation with the main category of the renewable energy system. Energy storage was the only category that had a strong relation with the recovery energy system. The correlations between each category were also defined. The results showed a strong positive correlation between LED lighting, wall insulation and platform screen doors. The correlation between energy storage and solar panels was also moderate. The weight of importance was chosen according to the priorities assigned to the main category of energy. The main category of the energy efficiency system had the highest priority at 62%. The renewable energy system had the second highest priority at 20%, and the recovery energy system had the lowest priority at 18%. The relative weight of each main element was calculated as follows:

- The LED lighting system had the importance weight of 612.6 and the relative weight of 29.1.
- The solar panel system had the importance weight of 203.6 and the relative weight of 9.7.
- The energy storage system had the weight of importance of 184. 4 and the relative weight of 8.8.
- Wall insulation had the weight of importance of 550.8 and the relative weight of 26.2.
- Platform screen doors system has weight of importance of 550.8 and relative weight of 26.2.

The details of QFD matrix for a “Best in Class” metro station are shown in Appendix C and Figure 23.

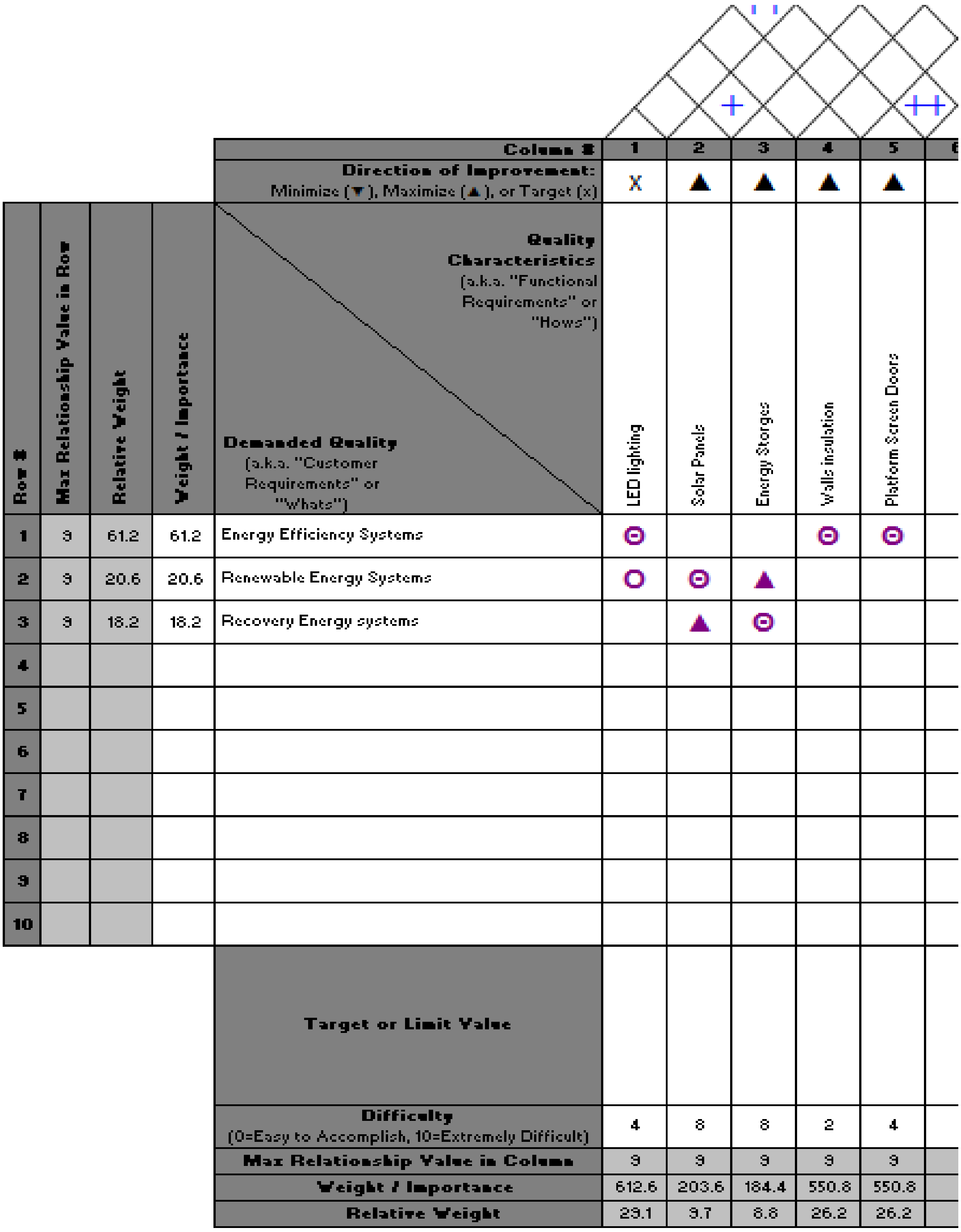


Figure 23: QFD Analysis of Energy Management in the Metro Station

Chapter 5: Development of the "Best in Class" Metro Station SAM

In this chapter, the "Best in Class" metro station benchmarking model or SAM is developed using the expert's data in the QFD matrix and the five elements of energy management (LED lighting, solar panels, energy storages, wall insulation and platform screen doors). The model developed in this study will enable both government and private sectors to benchmark and measure their energy management efficiency against the "Best in Class" model. This data will be entered on Excel spreadsheets to calculate capacity usage and the relative importance of each element to determine the level of integration with respect to energy management. The total project percentiles will be specified.

5.1 Expert Choice Data

In this section, the data that was gathered from the experts and analyzed using the Expert Choice software is entered on Excel spreadsheets. According to the results, system productivity was the superior criteria, receiving 50.2% of the votes. The next criterion was initial cost, which received almost 34.7% of the votes. The last criterion, environmental compatibility, garnered the lowest number of votes at 15.1%. The three main categories, energy efficiency system, energy renewable system and energy recovery systems, were prioritized with respect to three criteria. The results of this process showed that energy efficiency had the highest priority at almost 61.2%. The next main category, the renewable energy system, received 20.8% of the votes, and the third main category, energy recovery system, had 18.1% of the votes. Appendix C shows the data from the Expert Choice software entered on Excel spreadsheets.

5.2 Analysis of the QFD Data

The priorities assigned to the main categories are used to calculate the relative weights of the six elements of energy management (see Chapter 3, section 5). According to the QFD model, the relative weight of the LED lighting is 28.8. The relative weight of the solar panel is 9.7 and the relative weight of the energy storage is 8.7. The relative weights of wall insulation and platform screen doors were both 26.2.

5.3 LED Lighting Benchmarking Tool

The design data used for the LED lighting (see Chapter 3, section 1) will be used to create the ultimate benchmarking tool used to calculate the amount of LED lighting needed in the “Best in Class” metro station. Figure 24 shows three types of LED lighting: 8.5, 16, and 16.5 W lamps, which are used in different parts of the metro station. The required lux level in each area was determined by using the Illuminating Engineering Society (IES) codes. The lumen output per each LED lamp and utilization factor plus light loss factor was determined using the specification sheets provided by the LED lightings supply company. The usage capacity of LED lighting was calculated to measure the corresponding relative weight. For instance, if the metro station had a 100% usage capacity of LED lighting in all areas, then the relative weight would be 29.1.

"Best in Class" metro station benchmarking model for LED lighting system

Element	Type of system(Watt)	Location	A(m2)	F1(Lux)	Lu(lm)	Cu	LLF	n	N
Energy efficiency systems (LED lighting)	16	Entrance hall	2450	50	1500	0.9	0.99	4	23
	16.5	Platform	400	150	2100	0.9	0.99	4	8
	16.5	Rest rooms	140	150	2100	0.9	0.99	4	3
	8.5	Corridors	126	150	1100	0.9	0.99	4	5
	8.5	stairways	126	150	1100	0.9	0.99	4	5
Total	66		3,242.00					20	43

System	Element	Usage Capacity	Relative weight
Energy efficiency system	LED lighting	100%	29.1

N= Number of required LED Fixture
F1= Lux level required at target
A= Area of task location (m2)
Lu= Lumen output per LED lamps
Cu=Utilization coefficient of selected LED lamps
LLF= Light loss factor of selected LED lamps
n= number of lumps /fixture

Figure 24: “Best in Class” LED Lighting Benchmarking Tool

5.4 Solar Panel Benchmarking Tool

The total voltage needed for the LED lamps was used to calculate the number of solar panels needed for the solar panel’s ultimate benchmarking tools. The total voltages needed by the LED lighting system were used to calculate the requirements of both DC and AC. The off-grid solar system was used in the “Best in Class” metro station, which does not need batteries to store energy from the photovoltaic cells. Instead, the energy stored in the solar cells will be converted from DC to AC current to supply the electricity directly. The ampere-hour will be measured by the AC requirement to calculate the number of solar panels needed in both parallel and series arrangements. Moreover, because the full capacity of the solar panels is used to supply the electricity needed for the LED lighting, the relative weight of the 100% usage capacity of the solar panel is 9.8. Figure 25 shows the benchmarking tool for solar panels in SAM.

"Best in Class" metro station benchmarking model for Solar Panels

Element	Type of Element	Location	W/L	Total W/L	DC	AC	Amper-hour	System losses	Solar Radiation/day	Total Array Current	System Voltage	System AH	N in Parallel	N in series	Total Weight
Solar Panels	ZS- M-145	Entrance ha	1466.5	2508.6	25086.3	29513.3	1229.7	1475.7	3.0	489.7	1500.0	8.5	1.7	54.4	642.0
		Platform	529.1												
		Rest rooms	185.2												
		Corridors	163.9												
		stairways	163.9												

System	Element	Usage Capacity	Relative weight
Renewable energy system	Solar Panels	0%	0.0

W/L =Wattage needed /lumps * Number of lumps

DC requirement= (Total voltage)*(Hour/Day)

AC requirments=(DC requirement)/ (0.85)

N in series= Number of solar panels in series arrangement (Nominal PV system voltage / Nominal module voltage)

Amper-hour=Total DC&AC requirements /Voltage of system

Total weight= Weight of system *No of systems

System losses= 20% additional for Amper-hour due to system losses

N in Parallel= Number of Solar panels in Parallel arrangement(Total current required from solar arrays/current generated by modules at peak power)

Figure 25: “Best in Class” Solar Panels Benchmarking Tool

5.5 Flywheel Energy Storage Benchmarking Tool

The T-700 flywheel energy storage will be used in the “Best in Class” metro station because the specific energy that they store is higher than in other types of flywheels. The hollow cylinder was determined as the best shape to maximize the energy storage; it has a shape factor equal to 0.61. The maximum specific energy that can be stored in one flywheel is 666 Watt-hour/Kg. If the usage capacity of the energy storage were 100%, the relative weight would be 8.7. The stored energy can be used to supply the energy needed for the HAVC system or the lighting system. It can also be used to supply the energy needed in case of emergency situations. Figure 26 shows the flywheel energy storage benchmarking tool in System Application Matrix (SAM).

"Best in Class" metro station benchmarking model for flywheel energy

Element	Type of system	σm(Gpa)	Ks	ρ(Kg/m^3)	Esp=(Wh/kg)
Energy Recovey System(Energy storges)	Flywheel (T-700)	7	0.61	1780	666

System	Element	Capacity	Relative weight
Energy Recovery system	Energy storages	0%	0.0

σm=Maximum tensile strength (GPa)

Ks=Shape factor

ρ=Density of flywheel (kg/m3)

Esp=Maximum specific Energy (Wh/kg)

N=number of flywheel needed in metro station

Figure 26: Flywheel Energy Storage Benchmarking Tool

5.6 Wall Insulation Benchmarking Tool

Both polystyrene and rockwool materials are used as wall insulation in the "Best in Class" metro station benchmarking tool which is shown in Figure 27 (p.77). In order to find the optimal thickness of the wall insulation, which is also economic and efficient, the wall area, degree days of the target metro station, present-worth factor, thermal conductivity, system heating, material cost of insulation, thermal resistance and system efficiency were identified. If the insulation materials were used in the walls of the metro station, the usage capacity for walls' insulation would be 100%, and the relative weight would be 26.2.

5.7 Platform Screen Doors Benchmarking Tool

According to the Transport Guideline for Provision Public Transport report (2011), the platform length should be 175 m to accommodate a train 150 m in length. The side platforms were designed for the "Best in Class" metro station. The minimum width of the side platforms is 6 m, including a 3 m waiting area. In a train that is 150 m long, there are eight cars.

"Best in Class" metro station benchmarking model for Walls insulation

Element	Type of system(Watt)	DD, C°	Cf $/kg	PWF	k	Hu,J/kg	Ci,$	η	Rwt	Xopt(mm)
Energy efficiency systems (LED lighting)	Polystyrene	2055	0.06	9.09	0.032	3.6	29	0.99	0.592	154
	Rockwool	2055	0.06	9.09	0.042	3.6	107	0.99	0.592	78

System	Element	Usage Capacity	Relative weight
Energy efficiency system	Wall's insulation	100%	26.2

A=Area of walls (m2)	
DD=Degree days C°	Rw=Total wall resistance without thermal insulation
Cf = Fuel cost in $/kg	Ro=Outer air-film thermal resistance
PWF=([(1+r)]^N-1)/(r.([1+r)]^N)	η=System efficiency
K=Thermal conductivity	Rwt= Ri+Rw+Ro
Hu=Heating in (J/kg)	Ri=Inner air-film thermal resistance
Ci=Insulation material cost ($)	Xopt= Optimum insulation thickness(mm)

Figure 27: Wall Insulation Benchmarking Tool

Therefore, six platform screen doors are required per each train. There are two trains in the “Best in Class” metro station, each of which has 6 cars. Therefore, 12 platform screen doors are required as you can see in Figure 28. If the metro station used full-height platform screen doors, the usage capacity would be 100%, and the relative weight would be 26.2%.

"Best in Class" metro station benchmarking model for Platform Screen Doors

Element	Type of system	Type of Platform	L(m)	W(m)	Platform Area(m2)	Number of Cars	N of Door
Energy Efficiency System(Platform Screen Doors)	Full height	Side Platform	175	6	1050	6	12

System	Element	Usage Capacity	Relative weight
Energy efficiency system	Platform Screen Doors	100%	26.2

L= length of platform(m)
W=width of platform (m)
N of Cars= Number of cars per train
N of doors= Number of platform screen doors in both trains

Figure 28: Platform Screen Door Benchmarking Tool

5.8 Ultimate Integration Benchmarking Model (SAM)

The System Application Matrix (SAM), which is an ultimate integration-benchmarking model, is needed by both governmental and private sectors to measure the level of their success in energy management. In this study, the integration model was developed according to relative weights of five energy management elements in the metro station. If the relative weight of SAM is below 50, the energy management project is unsatisfactory, and both sectors need to retrofit their existing and new metro station projects to increase the level of integration. If the relative weight is between 50 and 70%, the status of the energy management in the project is developing, and it needs further appropriate actions to increase the level of integration. If the relative weight is between 70 and 90%, the status of energy management in metro station is at an acceptable level. Finally, if the total relative weight is between 90 and 100%, the status of energy management in the metro station is excellent and can be used as the ultimate model for the "Best in Class" metro station and future projects. Figure 29 shows the integration levels of metro stations and their assigned status.

Element Relative weight	Level	Remarks
Below 50	Unsatisfactory	Inadequate integration (Energy management not in desirable level)
50-70	Developing	Require further development on Energy management process
70-90	Acceptable	Energy managament in metro station is accaptable
90-100	Execllent	Substantial incopration of energy management in metro station
Elements	"Best in Class" relative weight	Currenet Project
LED lighting	29.1	
Solar Panels	9.8	
Energy Storages	8.7	
Walls' insulation	26.2	
Platform Screen Doors	26.2	
Total	100.0	

Figure 29: Ultimate Integration Benchmarking Model Ranking

Chapter 6: Conclusion and Recommendation

6.1 Conclusion

The “Best in Class” metro station benchmarking tool, which was entered on the Excel spreadsheets, will empower both government and private sectors to benchmark and measure their energy management efficiency in metro stations. This benchmarking tool can integrate energy practices in metro stations to measure the level of success in energy management. In creating this benchmarking tool—known as a System Application Matrix (SAM)—an optimal “Best in Class” metro station design, which has five energy management strategies, such as LED lighting, solar panels and so on, was created. In addition, both the AHP analysis and the QFD matrix were used to validate the optimal “Best in Class” metro station design and the SAM. The AHP analysis was used to prioritize the energy management main categories with respect to three criteria. Selected experts weighed the three main energy management categories (the energy efficiency system, the renewable energy system and the recovery energy system) and the three criteria (system productivity, initial cost of the system and environmental compatibility of the system) based on both their field and academic experiences. After prioritizing the experts’ judgments, system productivity (50.2% of votes) had the highest weight among the criteria. Additionally, the energy efficiency system, which was one of the main categories in the energy management system, had the highest priority (61.2%) compared to the two other main categories of the energy management system. The QFD matrix was used to find the relative importance of five energy management strategies with respect to the prioritizations of the main categories of energy management, which was analyzed in the AHP process. LED lighting had the highest level of importance by almost 29.1%. The next highest elements were wall insulation and platform screen doors by almost 26.2%. Solar panels, with 9.8%, and energy storages, with 8.7%, were the last two elements in terms of relative importance. The System Application Matrix is needed by both government and private sectors to measure the level of their success in energy management.

Finally, based on the relative weight of energy management elements, the integration model or SAM was developed. The metro stations with a relative weight of 50% or below have unsatisfactory energy management systems. If the relative weight of a metro station is in the range of 50% to 70%, they have a developing energy management status, and if the relative weight is between 70% and 90%, the energy management status is acceptable. Lastly, if the relative weight of a metro station is 90% to 100%, the energy management has an excellent status. Both government and private sectors can use this integration model or SAM to measure the importance weight of their energy management in metro stations. This way, they can focus on their weaknesses and strengths in order to improve their energy management strategies and reach the excellent status in the energy management model.

6.2 Recommendation

Energy management strategies are very important methods for decreasing the heavy dependence on non-renewable energy sources, which emit green gasses. Therefore, it is essential for private and government sectors to implement more energy management practices in the construction of public buildings, such as metro stations. As a result, further research into these energy management elements is compulsory. The following recommendations have been projected for the improvement of a SAM:

- The optimal design should be improved based on environmental conditions such as temperature, humidity and so on. For example, in a hot environment, such as the UAE, energy management systems should focus on air conditioning systems.
- The optimal design should be enhanced based on the availability and accessibility of materials. For instance, solar panels are useful in countries with high sun intensities.
- Structural and construction design codes used in countries are different. The SAM users should be careful to use the optimal design according to the code of practices used in the target country.
- The focus of this study is on only five energy management elements. The SAM can be extended to more energy management elements.
- There are only three criteria and three main categories of energy management used in this paper. For further research and study, criteria and categories can be extended.
- There were only six experts chosen to do the AHP analysis. In order to have more consistency and reliable results, the number of experts can be increased.

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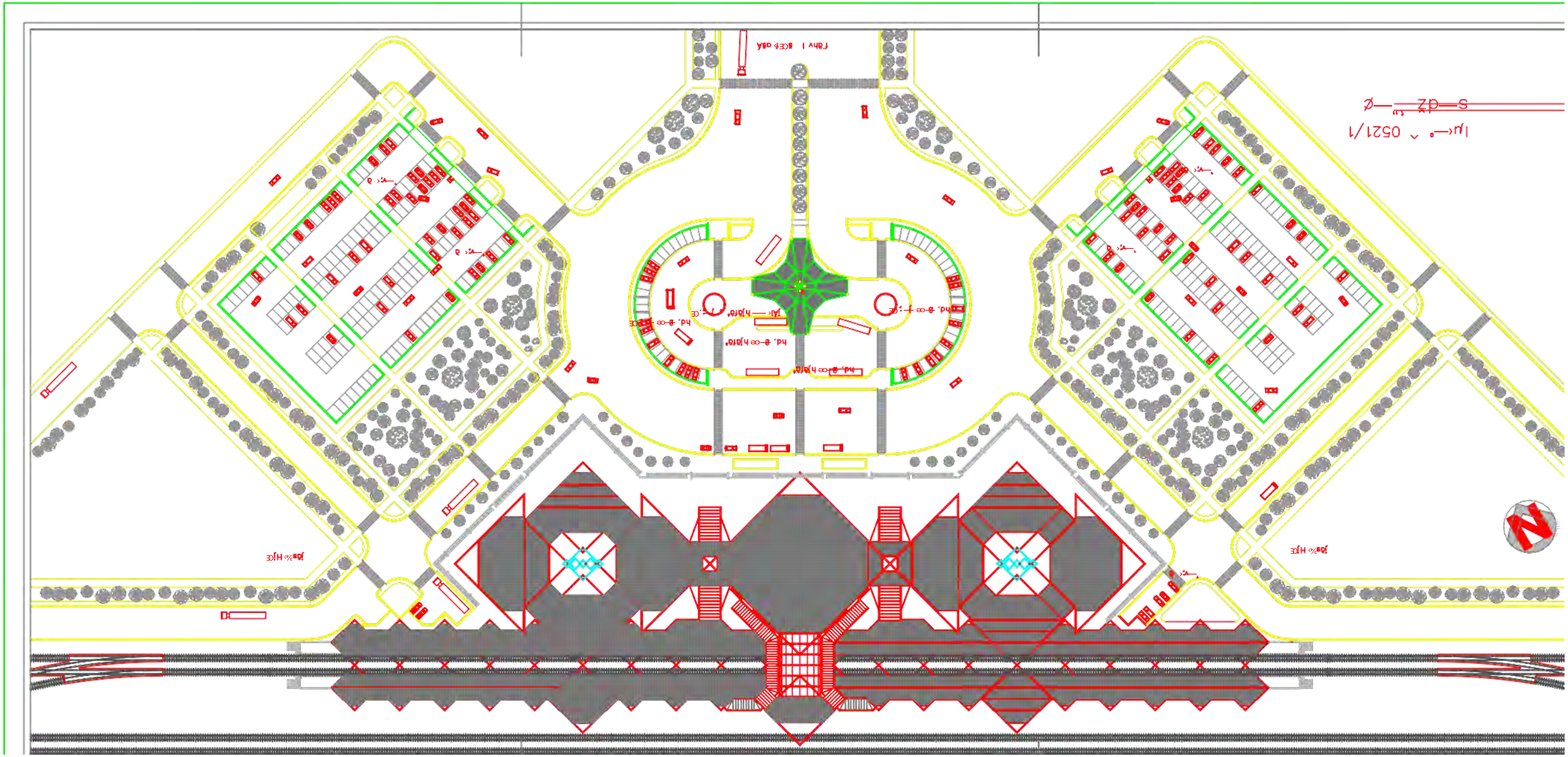
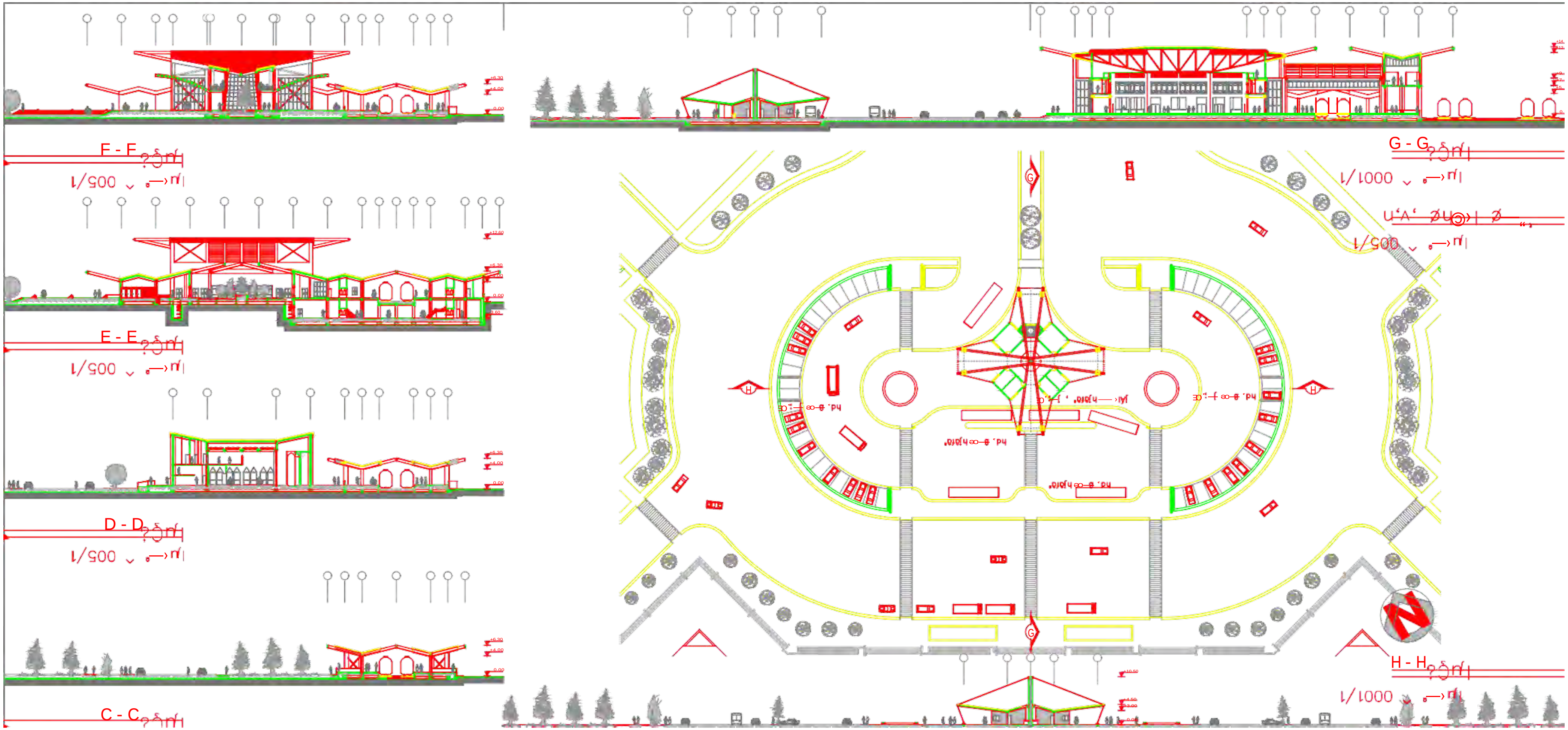
Appendix A: Architectural Drawings of "Best in Class" metro station

Appendix A: Architectural Drawing of "Best in Claaa" metro station



Architctural Drawing
Drawing title : Plan View
Project: Vanak metro station(Tehran)
Designer: Majid Karimi
Consultant Company: Karmi group

Appendix A: Architectural Drawing of "Best in Class" metro station



Architectural Draings
Drwaing title: Section view
Project Name: Vanak metro(Tehran)
Designer: Majid Karimi
Consultant Company: Karimi group

Appendix B: Expert Panel Input

An Expert Panel for Energy management system in metro stations

Name: Danish Faraz

Position: Electrical Engineer

Organization: Abdul Rahim Consultation Company

Years of experiences: 10 years

Ranking key:

1	2 3		4	5	6	7	8	9
Equally Significant	Equally significant to moderately more significant	Moderately more significant	Moderately to strongly more significant	Strongly more significant	Strongly to very strongly significant	Very strongly more significant	Very strongly to extremely more significant	Extremely more significant

Ranking Example:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost of System**	**Environmental Compatibility of System**
System Productivity	1	5	8
Initial Cost of System	1/5	1	4
Environmental Compatibility of System	1/8	1/4	1

- In the planning phase of Metro Stations, the System Productivity is **strongly more significant** than the initial cost of applying the system.
- In the planning phase of Metro Stations, the initial cost of Energy Management Systems Elements is **moderately to strongly more significant** than the environmental compatibility of system. Rank the following expert panels according to your judgment:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost**	**Environmental Compatibility**
System Productivity	1	1/3	5
System Initial Cost	3	1	7
System Environmental Compatibility	1/5	1/7	1

Criteria	**System Productivity**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	6	6
Renewable Energy Elements (REE)	1/6	1	1
Recovery Energy Elements (RCEE)	1/6	1	1

Criteria	**Initial Cost of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	8	7
Renewable Energy Elements (REE)	1/8	1	1/2
Recovery Energy Elements (RCEE)	1/7	2	1

Criteria	**Environmental Compatibility of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	1/5	1/7
Renewable Energy Elements (REE)	5	1	1/2
Recovery Energy Elements (RCEE)	7	2	1

An Expert Panel for Energy management system in metro stations

Name: Hamidreza Salimi

Position: Mechanical Engineer

Organization: Abdul Rahim Consultation Company

Years of experiences: 7 years

Ranking key:

1	2 3		4	5	6	7	8	9
Equally Significant	Equally significant to moderately more significant	Moderately more significant	Moderately to strongly more significant	Strongly more significant	Strongly to very strongly significant	Very strongly more significant	Very strongly to extremely more significant	Extremely more significant

Ranking Example:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost of System**	**Environmental Compatibility of System**
System Productivity	1	5	8
Initial Cost of System	1/5	1	4
Environmental Compatibility of System	1/8	1/4	1

- In the planning phase of Metro Stations, the System Productivity is **strongly more significant** than the initial cost of applying the system.
- In the planning phase of Metro Stations, the initial cost of Energy Management Systems Elements is **moderately to strongly more significant** than the environmental compatibility of system. Rank the following expert panels according to your judgment:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost**	**Environmental Compatibility**
System Productivity	1	5	1
System Initial Cost	1	1	5
System Environmental Compatibility	1/5	1/5	1

Criteria	**System Productivity**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	5	8
Renewable Energy Elements (REE)	1/5	1	3
Recovery Energy Elements (RCEE)	1/8	1/5	1

Criteria	**Initial Cost of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	5	7
Renewable Energy Elements (REE)	1/5	1	2
Recovery Energy Elements (RCEE)	1/7	1/2	1

Criteria	**Environmental Compatibility of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	1/7	1/5
Renewable Energy Elements (REE)	7	1	3
Recovery Energy Elements (RCEE)	5	1/3	1

An Expert Panel for Energy management system in metro stations

Name: Ali Vahabpour

Position: Project Manager

Organization: Abdul Rahim Consultation Company

Years of experiences: 16 years

Ranking key:

1	2 3		4	5	6	7	8	9
Equally Significant	Equally significant to moderately more significant	Moderately more significant	Moderately to strongly more significant	Strongly more significant	Strongly to very strongly significant	Very strongly more significant	Very strongly to extremely more significant	Extremely more significant

Ranking Example:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost of System**	**Environmental Compatibility of System**
System Productivity	1	5	8
Initial Cost of System	1/5	1	4
Environmental Compatibility of System	1/8	1/4	1

- In the planning phase of Metro Stations, the System Productivity is **strongly more significant** than the initial cost of applying the system.
- In the planning phase of Metro Stations, the initial cost of Energy Management Systems Elements is **moderately to strongly more significant** than the environmental compatibility of system. Rank the following expert panels according to your judgment:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost**	**Environmental Compatibility**
System Productivity	1	4	1/4
System Initial Cost	4	1	8
System Environmental Compatibility	1/4	1/8	1

Criteria	**System Productivity**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	4	6
Renewable Energy Elements (REE)	1/4	1	3
Recovery Energy Elements (RCEE)	1/6	1/3	1

Criteria	**Initial Cost of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	4	6
Renewable Energy Elements (REE)	1/4	1	2
Recovery Energy Elements (RCEE)	1/6	1/2	1

Criteria	**Environmental Compatibility of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	1/3	1/3
Renewable Energy Elements (REE)	3	1	1
Recovery Energy Elements (RCEE)	3	1	1

An Expert Panel for Energy management system in metro stations

Name: Dr. Ghassan Abu-Lebdeh

Position: Associated Professor in Civil Engineering Department

Organization: American University of Sharjah

Years of experiences: 16 years in field of transportation and urban design

Ranking key:

1	2	3	4	5	6	7	8	9
Equally Significant	Equally significant to moderately more significant	Moderately more significant	Moderately to strongly more significant	Strongly more significant	Strongly to very strongly significant	Very strongly more significant	Very strongly to extremely more significant	Extremely more significant

Ranking Example:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost of System**	**Environmental Compatibility of System**
System Productivity	1	5	8
Initial Cost of System	1/5	1	4
Environmental Compatibility of System	1/8	1/4	1

- In the planning phase of Metro Stations, the System Productivity is **strongly more significant** than the initial cost of applying the system.
- In the planning phase of Metro Stations, the initial cost of Energy Management Systems Elements is **moderately to strongly more significant** than the environmental compatibility of system. Rank the following expert panels according to your judgment:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost**	**Environmental Compatibility**
System Productivity	1	7	8
System Initial Cost	1/7	1	3
System Environmental Compatibility	1/8	1/3	1

Criteria	**System Productivity**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	6	7
Renewable Energy Elements (REE)	1/6	1	4
Recovery Energy Elements (RCEE)	1/7	1/4	1

Criteria	**Initial Cost of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	7	8
Renewable Energy Elements (REE)	1/7	1	1/3
Recovery Energy Elements (RCEE)	1/8	3	1

Criteria	**Environmental Compatibility of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	1/8	1/6
Renewable Energy Elements (REE)	8	1	1/3
Recovery Energy Elements (RCEE)	6	3	1

An Expert Panel for Energy management system in metro stations

Name: Dr. Md Marouf Mortula

Position: Associated Professor in Civil Engineering Department

Organization: American University of Sharjah

Years of experiences: 10 years in field of enviromental and sustainbility design

Ranking key:

1	2	3	4	5	6	7	8	9
Equally Significant	Equally significant to moderately more significant	Moderately more significant	Moderately to strongly more significant	Strongly more significant	Strongly to very strongly significant	Very strongly more significant	Very strongly to extremely more significant	Extremely more significant

Ranking Example:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost of System**	**Environmental Compatibility of System**
System Productivity	1	5	8
Initial Cost of System	1/5	1	4
Environmental Compatibility of System	1/8	1/4	1

- In the planning phase of Metro Stations, the System Productivity is **strongly more significant** than the initial cost of applying the system.
- In the planning phase of Metro Stations, the initial cost of Energy Management Systems Elements is **moderately to strongly more significant** than the environmental compatibility of system. Rank the following expert panels according to your judgment:

Pairwise Comparison of Criteria	System Productivity	Initial Cost	Environmental Compatibility
System Productivity	1	2	3
System Initial Cost	1/2	1	2
System Environmental Compatibility	1/3	1/2	1

Criteria	**System Productivity**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	5	3
Renewable Energy Elements (REE)	1/5	1	1/3
Recovery Energy Elements (RCEE)	1/3	3	1

Criteria	**Initial Cost of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	3	2
Renewable Energy Elements (REE)	1/3	1	1/2
Recovery Energy Elements (RCEE)	1/2	2	1

Criteria	**Environmental Compatibility of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	1/4	1/3
Renewable Energy Elements (REE)	4	1	1/2
Recovery Energy Elements (RCEE)	3	2	1

An Expert Panel for Energy management system in metro stations

Name: Dr. Yousef H.Zurigat

Position: Associated Professor in Civil Engineering Department

Organization: American University of Sharjah

Years of experiences: 25 years in field of mechanical and energy management design

Ranking key:

1	2 3		4	5	6	7	8	9
Equally Significant	Equally significant to moderately more significant	Moderately more significant	Moderately to strongly more significant	Strongly more significant	Strongly to very strongly significant	Very strongly more significant	Very strongly to extremely more significant	Extremely more significant

Ranking Example:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost of System**	**Environmental Compatibility of System**
System Productivity	1	5	8
Initial Cost of System	1/5	1	4
Environmental Compatibility of System	1/8	1/4	1

- In the planning phase of Metro Stations, the System Productivity is **strongly more significant** than the initial cost of applying the system.
- In the planning phase of Metro Stations, the initial cost of Energy Management Systems Elements is **moderately to strongly more significant** than the environmental compatibility of system. Rank the following expert panels according to your judgment:

Pairwise Comparison of Criteria	**System Productivity**	**Initial Cost**	**Environmental Compatibility**
System Productivity	1	7	3
System Initial Cost	1/7	1	1/5
System Environmental Compatibility	1/3	5	1

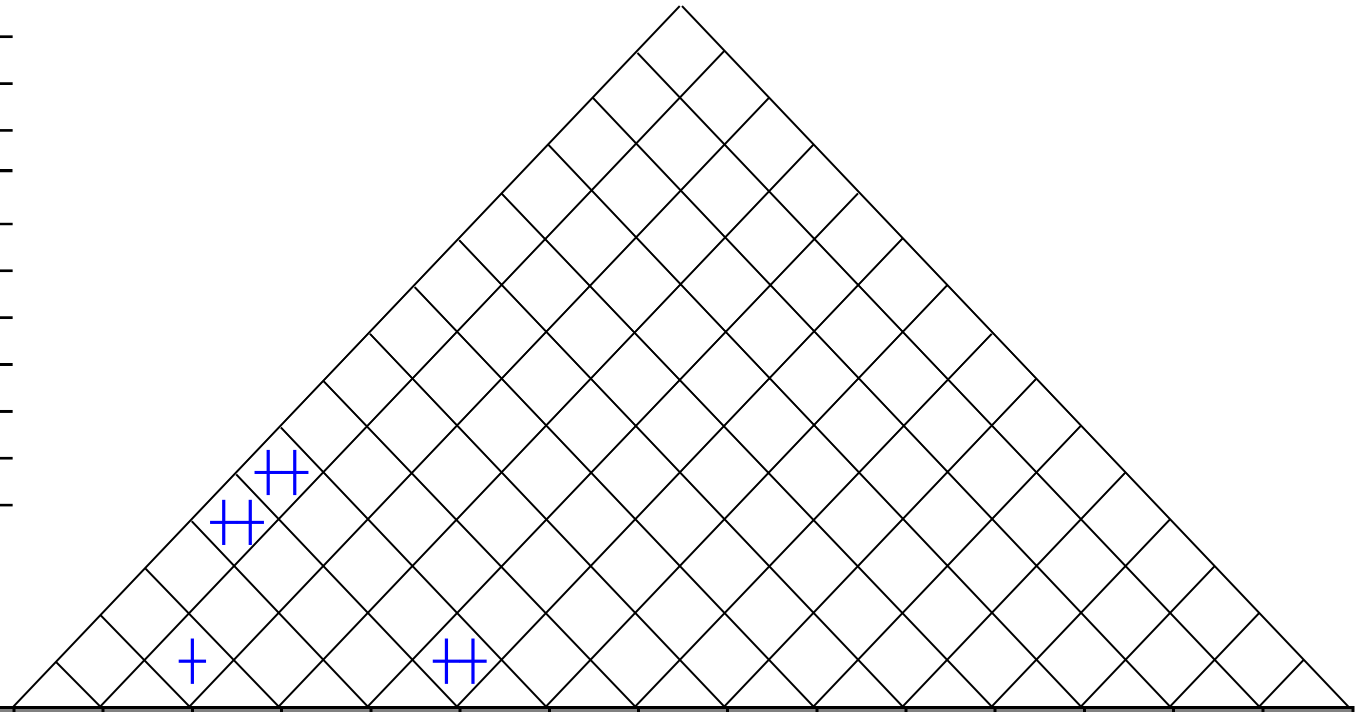
Criteria	**System Productivity**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	8	7
Renewable Energy Elements (REE)	1/8	1	8
Recovery Energy Elements (RCEE)	1/7	1/8	1

Criteria	**Initial Cost of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	7	6
Renewable Energy Elements (REE)	1/7	1	1/2
Recovery Energy Elements (RCEE)	1/6	2	1

Criteria	**Environmental Compatibility of System**		
Elements	Energy Efficient Elements	Renewable Energy Elements	Recovery Energy Elements
Energy Efficient systems (EES)	1	1/8	1/5
Renewable Energy Elements (REE)	8	1	7
Recovery Energy Elements (RCEE)	5	1/7	1

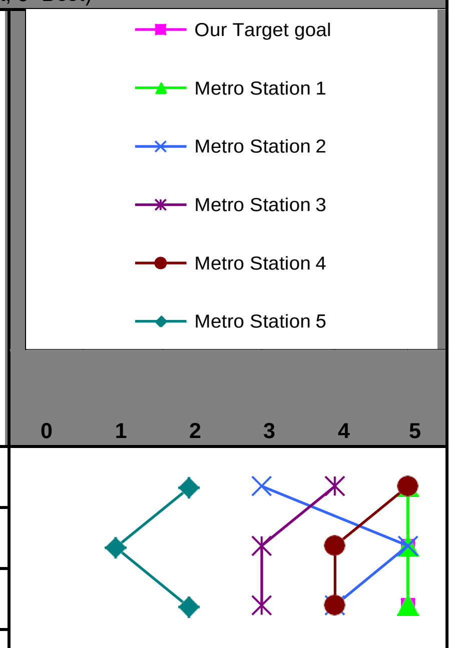
Appendix C: Quality Function Development Matrix for “Best in Class” Metro Station

Title: Benchmarking of Energy Management Systems in Metro Stations
Author: Samira Rajabi
Date: 6/3/2014
Notes:



Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Our Target goal	Metro Station 1	Metro Station 2	Metro Station 3	Metro Station 4	Metro Station 5
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	x	▲	▲	▲	▲											**Competitive Analysis** (0=Worst, 5=Best)					
				Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / **Demanded Quality** (a.k.a. "Customer Requirements" or "Whats")	LED lighting	Solar Panels	Energy Storges	Walls insulation	Platform Screen Doors																
1	9	61.2	61.2	Energy Efficiency Systems	Θ			Θ	Θ											5	5	3	4	5	2
2	9	20.6	20.6	Renewable Energy Systems	O	Θ	▲													5	5	5	3	4	1
3	9	18.2	18.2	Recovery Energy systems		▲	Θ													5	5	4	3	4	2
4																									
5																									
6																									
7																									
8																									
9																									
10																									
				Target or Limit Value																					
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	4	8	8	2	4																
				Max Relationship Value in Column	9	9	9	9	9																
				Weight / Importance	612.6	203.6	184.4	550.8	550.8																
				Relative Weight	29.1	9.7	8.8	26.2	26.2																



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Appendix D: System Application System Matrix (SAM) Example in Dubai Metro Stations

Appendix D : SAM Example in Dubai Metro Stations

Experts' Choice Analysis

Level 1	Alts	Prty
System Productivity (L: .502)	Energy Efficien	0.339
System Productivity (L: .502)	Renewable Energ	0.064
System Productivity (L: .502)	Recovery Energy	0.055
Enviromental Compatibility of System (L: .151)	Energy Efficien	0.038
Enviromental Compatibility of System (L: .151)	Renewable Energ	0.102
Enviromental Compatibility of System (L: .151)	Recovery Energy	0.084
Initial Cost of System (L: .347)	Energy Efficien	0.234
Initial Cost of System (L: .347)	Renewable Energ	0.042
Initial Cost of System (L: .347)	Recovery Energy	0.042

Sum of Prty	Alts			
Level 1	Energy Efficien	Recovery Energy	Renewable Energy	Grand Total
Enviromental Compatibility of System (L: .151)	0.038	0.084	0.102	0.224
Initial Cost of System (L: .347)	0.234	0.042	0.042	0.318
System Productivity (L: .502)	0.339	0.055	0.064	0.458
Grand Total	0.611	0.181	0.208	1

Sum of Prty	Level 1			
Alts	Enviromental Compatibility of System (L: .151)	Initial Cost of System (L: .347)	System Productivity (L: .502)	Grand Total
Energy Efficien	0.038	0.234	0.339	0.611
Recovery Energy	0.084	0.042	0.055	0.181
Renewable Energ	0.102	0.042	0.064	0.208
Grand Total	0.224	0.318	0.458	1

QFD Analysis

Releative importance of elements

Elements of Energy Management	weight/importance	Relative Importance
Energy Efficiency System	61.1	61.1
Renewable energy system	20.8	20.8
Recovery Energy system	18.1	18.1

Relative importance of systems

System of Energy Management	**Rating of relations with elements in columns**	**weight/importance**	**Relative importance**
LED lighting System	9	612.3	29.1
	3		
Solar Panels	9	205.3	9.8
	1		
Energy Storages	1	183.7	8.7
	9		
Walls' insulation	9	549.9	26.2
Platform Screen Doors	9	549.9	26.2

Appendix D : SAM Example in Dubai Metro Stations

"Best in Class" metro station benchmarking model for LED lighting system

Element	Type of system(Watt)	Location	A(m2)	F1(Lux)	Lu(lm)	Cu	LLF	n	N
Energy efficiency systems (LED lighting)	16	Entrance hall	2450	50	1500	0.9	0.99	4	23
	16.5	Platform	400	150	2100	0.9	0.99	4	8
	16.5	Rest rooms	140	150	2100	0.9	0.99	4	3
	8.5	Corridors	126	150	1100	0.9	0.99	4	5
	8.5	stairways	126	150	1100	0.9	0.99	4	5
Total	66		3,242.00					20	43

System	Element	Usage Capacity	Relative weight
Energy efficiency system	LED lighting	100%	29.1

N= Number of required LED Fixture

n= number of lumps /fixture

F1= Lux level required at target

LLF= Light loss factor of selected LED lamps

A= Area of task location (m2)

Cu=Utilization coefficient of selected LED lamps

Lu= Lumen output per LED lamps

Appendix D : SAM Example in Dubai Metro Stations

"Best in Class" metro station benchmarking model for Solar Panels

Element	Type of Element	Location	W/L	Total W/L	DC	AC	Amper-hour	System losses	Solar Radiation/day	Total Array Current	System Voltage	System AH	N in Parallel	N in series	Total Weight
Solar Panels	ZS- M-145	Entrance hall	1466.5	2508.6	25086.3	29513.3	1229.7	1475.7	3.0	489.7	1500.0	8.5	1.7	54.4	642.0
		Platform	529.1												
		Rest rooms	185.2												
		Corridors	163.9												
		stairways	163.9												

System	Element	Usage Capacity	Relative weight
Renewable energy system	Solar Panels	0%	0.0

W/L =Wattage needed /lumps * Number of lumps

DC requirement= (Total voltage)*(Hour/Day)

AC requirments=(DC requirement)/ (0.85)

N in Parallel= Number of Solar panels in Parallel arrangement(Total current required from solar arrays/current generated by modules at peak power)

N in series= Number of solar panels in series arrangement (Nominal PV system voltage / Nominal module voltage)

Amper-hour=Total DC&AC requirements /Voltage of system

Total weight= Weight of system *No of systems

Appendix D : SAM Example in Dubai Metro Stations

"Best in Class" metro station benchmarking model for flywheel energy storages

Element	Type of system	σm(Gpa)	Ks	ρ(Kg/m^3)	Esp=(Wh/kg)
Energy Recovey System(Energy storges)	Flywheel (T-700)	7	0.61	1780	666

System	Element	Capacity	Relative weight
Energy Recovery system	Energy storages	0%	0.0

σm=Maximum tensile strength (GPa)

Ks=Shape factor

ρ=Density of flywheel (kg/m3)

Esp=Maximum specific Energy (Wh/kg)

N=number of flywheel needed in metro station

Appendix D : SAM Example in Dubai Metro Stations

"Best in Class" metro station benchmarking model for Walls insulation

Element	Type of system(Watt)	DD, C°	Cf $/kg	PWF	k	Hu,J/kg	Ci,$	η	Rwt	Xopt(mm)
Energy efficiency systems (LED lighting)	Polystyrene	2055	0.06	9.09	0.032	3.6	29	0.99	0.592	154
	Rockwool	2055	0.06	9.09	0.042	3.6	107	0.99	0.592	78

System	Element	Usage Capacity	Relative weight
Energy efficiency system	Wall's insulation	100%	26.2

Rw=Total wall resistance without thermal insulation

A=Area of walls (m2)

Ro=Outer air-film thermal resistance

DD=Degree days C°

η=System efficiency

Ci=Insulation material cost ($)

Cf = Fuel cost in $/kg

Rwt= Ri+Rw+Ro

Hu=Heating in (J/kg)

PWF=(〖(1+r)〗 ^N-1)/(r.(〖1+r)〗 ^N

Ri=Inner air-film thermal resistance

K=Thermal conductivity

Xopt= Optimum insulation thickness(mm)

Appendix D : SAM Example in Dubai Metro Stations

"Best in Class" metro station benchmarking model for Platform Screen Doors

Element	Type of system	Type of Platform	L(m)	W(m)	Platform Area(m2)	Number of Cars	N of Door
Energy Efficiency System(Platform Screen Doors)	Full height	Side Platform	175	6	1050	6	12

System	Element	Usage Capacity	Relative weight
Energy efficiency system	Platform Screen Doors	100%	26.2

L= length of platform(m)

W=width of platform (m)

N of Cars= Number of cars per train

N of doors= Number of platform screen doors in both trains

Appendix D : SAM Example in Dubai Metro Stations

System Application Matrix(SAM) for Dubai metro stations

Element Relative weigh	Level	Remarks
Below 50	Unsatisfactory	Inadequate integration (Energy management not in desirable level)
50-70	Developing	Require further development on Energy management process
70-90	Acceptable	Energy managament in metro station is accaptable
90-100	Execllent	Substantial incopration of energy management in metro station

Elements	"Best in Class" relati	Currenet Project (Dubai metro stations)
LED lighting	29.1	29.1
Solar Panels	9.8	0.0
Energy Storages	8.7	0.0
Walls' insulation	26.2	26.2
Platform Screen Doors	26.2	26.2
Total	100.0	**81.5**

Energy Manegemnet in Dubai metro stations is Acceptable

Vita

Samira Rajabi was born in December 12, 1989, in Iran, Tehran. She moved to United Arab Emirates in 2004. She was graduated with a bachelor's of Civil Engineering from American University of Sharjah in 2012. Currently, she is doing her Master degree in Engineering system Management and working as a cost estimator in Dutco Construction Company.