ISTANBUL TECHNICAL UNIVERSITY★ ENERGY INSTITUTE

ENERGY PERFORMANCE OF BUILDING INTEGRATED SOLARWALL SYSTEM
CASE STUDY: SABİHA GÖKÇEN AIRPORT

M.Sc. THESIS

Ömer AYDEDE

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

HAVA GEÇİŞLİ GÜNEŞ KOLLEKTÖRÜ UYGULAMALI BİNADA ENERJİ PERFORMANSI DEĞERLENDİRMESİ
DURUM DEĞERLENDİRMESİ: SABİHA GÖKÇEN HAVALİMANI

YÜKSEK LİSANS TEZİ

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Enerji Bilim ve Teknoloji Anabilim Dalı

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Ömer AYDEDE, a M.Sc. student of ITU Energy Institute student ID 301101030, succesfully defended the thesis entitled **'ENERGY PERFORMANCE OF BUILDING INTEGRATED SOLARWALL SYSTEM',** which he prepared after fullfilling the requirements specified in the associated legistations, before the jury whose signatures are below.

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FOREWORD

Hereby, I would like to express my gratitude's to my advisor Assoc. Prof. Dr. Hatice Sözer for her patience and guidance with great understanding of my tough situation about my work. I want to thank my colleagues in ISG Yatırım Yapım ve İşlt. A.Ş. for their support and sharing their documentations to help my thesis study. I also want to thank my friend Onur Serçinoğlu for his help with the proofreading of my thesis.
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January 2014 Ömer AYDEDE
(Mechanical Engineer)

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ABBREVIATIONS

DHW	**:** Domestic water heating
PV	**:** Photovoltaic
CIP	**:** Commercial important person
HVAC	**:** Heating ventilation air- conditioning
COP	**:** Coefficient of Performance
TRIGEN	**:** Trigeneration system
AHU	**:** Air handling unit
BMS	**:** Building management system
VRV	**:** Variable refrigerant volume
FCU	**:** Fan coil unit
BSRIA	**:** Solarwall automation system
UTC	**:** Unglazed transpired collector
RG	**:** Reference power

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F_{uf}	**:** Equipment utilization factor
F_{lf}	**:** Equipment load factor
C_p	**:** Specific heat of air **(**kJ/kg $^{\circ}$C)
ρ	**:** Air density **(**kg/m^3)
ΔT	**:** Humidity of air (kg/kg)
U_{value}	**:** Heat transfer coefficient (W/m^2K**)**
SHR	**:** Sensible heat ratio
V	**:** Speed of air (m/s)
F	**:** Area (m^2)
Q_f	**:** Amount of fresh air flow rate **(**m^3/h)
α	**:** Absorptivity of solarwall
$f_{utility}$	**:** Utilization factor
η	**:** Efficiency
G_{tilt}	**:** Tilted solar energy
R_{wall}	**:** Resistance of wall (m^2 $^{\circ}$C /W)
ε	**:** Emissivity
σ	**:** Stefan-Boltzmann constant (W/ m^2 K^4)

ENERGY PERFORMANCE OF BUILDING INTEGRATED SOLARWALL SYSTEM
CASE STUDY: SABİHA GÖKÇEN AIRPORT

SUMMARY

Most of the energy needs of the world is supplied via fossil fuels. The greenhouse gases that arise as a result of fossil fuel consumption leads to increases in the temperature of the world. For this reason, buildings that consume green energy have gained increasing importance. Solar energy systems are of preference when green energy consumption in buildings is desired. In this study, the use of solar energy is investigated for supplying of some of the heating energy needs of departing floor of Sabiha Gökçen Airport. Integration of the unglazed transpired collector system is developed and heating load reductions in the demand of places with fresh air need as a result of heating of the intake air during winter months are calculated. The model of the building is drawn in Ecotect Analysis 2011 software in order to determine the heating needs of the place during winter months. In the building model, the Departures Waiting Area is denoted as Zone 8. This zone is studied in more detail in software compared to other zones, including the determination of the materials and their heat conductivity coefficients used in walls, glaze and ceiling components. Zone 8 is fed via the Air handling units located on the mezzanine floor. The Air handling units obtain the fresh air from the terrace area on the mezzanine floor. This area is faced toward southwest direction and has a vertical wall. This wall has no shade introducing objects in front of it, so its usable area of 1420 square-meters is a good spot for solarwall application. This surface is divided into East Solarwall part and West Solarwall parts. The air entering the Air Handling Units is controlled via three modulation dampers. In winter, the damper connected to the Solarwall surface is active.

The number of passengers is determined according to the number of passenger entrance doors on the departures floor. The minimum amount of fresh air need is calculated according to number of passengers per hour. This fresh air need is equal to the air flow rate through the Solarwall system. The fresh air need of Zone 8 is calculated as 54625 m^3. The energy gains of Solarwall system are calculated by using Retscreen SAH3 software and solution of energy balances. Using the Retscreen software, it is first determined how much solar energy is received horizontal on the determined Solarwall surface. After finding out how much usable solar energy is obtained, the efficiency of the air collector is calculated. The efficiency of the collector depends on the air flow rate per square-meter and ambient air wind flow. The efficiency of the collectors is found to be around 40 %. This value is validated with the efficiency graph obtained from Retscreen's calculations for the Solarwall. The solarwall system additionally provides energy savings via recycling the lost heat from the walls. The energy savings as a result of Solarwall usage are calculated by using Retscreen SAH3 software. The calculations are principally validated with energy balance calculations. We chose Retscreen software as it was

developed for this system and the effect of wind is taken into account in calculations. The annual Solarwall energy is 393 Mwh. However, the total energy savings reduce to 231 Mwh since some of the regained energy is not needed in May, September and October. We only meet 12.8 % of the annual heating requirements of Zone 8 by Solarwall application. Within the investment costs of Solarwall, collectors, labor and others (ducts, cables) are included. The first investment includes 60 % for collectors, 33 % for labor and 6 % for other costs. It is possible to reduce the initial investment costs by 30 % with energy support programs of the Government. The payback time is calculated as approximately 14 years. The main reason for this value is that the system does not function with 100 % of fresh air and the high cost of collectors. Energy efficiency classes are defined for buildings. According to this classification, the per square meter energy consumption of the building classifies it as a B-class with a value of 70 kWh/m^2. After the application of Solarwall system, this value reduces to 64.9 kWh/m^2. The reduction in the emission into the atmosphere is also calculated when Solarwall system is applied. Since the heating of the building is mainly supplied by natural gas operated boilers, reductions in methane gas emissions are calculated as well. As a result, a total of 51.38 tons of carbon dioxide emission reduction is determined.

HAVA GECİŞLİ GÜNEŞ PANELİ UYGULAMALI BİNALARDA ENERJİ PERFORMANSI DEĞERLENDİRMESİ DURUM DEĞERLENDİRMESİ: SABİHA GÖKÇEN HAVALİMANI

ÖZET

Enerji ihtiyaclarının büyük bölümü dünyada fosil kaynaklardan karşılanmaktadır. Fosil yakıtların yanması sonucu ortaya çıkan sera gazları dünyamızın ısınmasına sebep olmaktadır. Bu sebepten yeşil enerji kullanan binaların önemi gün geçtikçe artmaktadır. Binalarda yeşil enerji kullanımı için güneş enerjisi sistemleri tercih edilebilir. Güneş enerji sistemlerinden yararlanma metotları farklıdır. Ana başlık olarak aktif güneş enerji sistemleri ve pasif güneş enerji sistemleri olarak ayrılabilir. Aktif güneş enerji sistemlerinde sistemin çalışması için dışarıdan enerji verilmesi gerekirken pasif güneş enerji sistemlerinde bu enerjiye gerek yoktur. Bu tezde pasif enerji sistemlerinden bahsedilmiş ve geçişli hava sistemi üzerinde çalışma yapılmıştır. Geçişli hava sistemi binaya giren taze havayı ısıtarak enerji tasarrufu sağlayan güneş enerji sistemidir. Özel kaplaması sayesinde yüksek absorpsiyon oranına sahiptir. Dikey olarak kullanılmasından dolayı binaların kullanılmayan cephelerine monte edilebilmekte ve renk seçimine bağlı olarak bina estetiğini bozmamaktadır. Bununla beraber sistemin herhangi bir bakım maliyeti bulunmamaktadır. Yutdışında bir çok uygulaması olan bu sistem kolaylıkla klima santrallerine veya diğer mekanik sistemlerine entegre edilebilmektedir. Isıtmanın kış aylarında yapılmasından kaynaklı olarak bu sistemin verimi iklimin kışları soğuk ve bulutsuz yerlerde ve taze hava ihtiyacı yüksek olan binalarda yüksektir. Sistemin verimli çalışabilmesi için güney cepheleri tercih edilmeli ve kurulan panellere gölge yapacak herhangi bir nesne bulunmamalıdır. Ayrıca bu sistem fotovoltaik modüllerle birlikte entegre edildiğinde fotovoltaik modüllerin arkasında ısı oluşmasında kaynaklı verimi düşüşünü engellediği ve hibrit denilen bu sistemin veriminin diğer klasik sistem verimine göre daha iyi olduğu belirtilmiştir. Fakat geçişli hava sistemi yaz aylarında çalışmadığından klima santrallerinde by-pass damperi açılarak taze hava direk dışarından alınır. Yaz aylarında panellerde toplanan yüksek güneş enerjisi panellerin üstü açılarak dışarıya verilmekte ve bina sistemine herhangi bir katkısı olmamaktadır. Oysa ki bu enerji soğutmada kullanılırsa sistem daha fazla bir verimle çalışmış olacaktır. Bu tezde hava geçişli sistemi incelemek üzere örnek çalışma olarak Sabiha Gökçen havalimanın giden yolcu bekleme salonunun güneş enerjisi ile ısıtma yükünün bir bölümünün karşılanması ele alınmıştır. Geliştirilen have geçişli (Solarwall) sisteminin entegrasyonu çalışmada yapılmış ve taze hava ihtiyacı olan mahalin kış aylarında içeri alınan havanın ısıtılması sonucu düşürülen ısıtma ihtiyacı hesaplanmıştır. Mahalin kış aylarında ısıtma ihtiyacını belirlemek için binanın çizimi Ecotect Analysis 2011 programında yapılmıştır. Bina modellemesinde giden katı yolcu bekleme salonu Zone 8 olarak belirlendi. Bu zone program içinde diğer zonlara göre daha fazla detaylandırıldı. Bu detaylandırmanın içinde duvar, cam, tavan gibi komponentlerin malzemelerinin atanması ve bunların ısı geçirgenlik katsayılarının belirlenmesi vardır. Zone 8'i asma katta bulunan klima santralleri beslemektedir. Klima santralleri taze havayı asma katta bulunan teras bölgesinden almaktadır. Teras

bölgesinde bulunan bu bölge güney-batı yönünde olup dikey duvardır. Bu duvarın önünde gölge yapacak hiç bir nesne bulunmadığı gibi kullanılabilir alanı 1420 m^2 gibi gayet uygun bir alandır. Bu yüzey Solarwall alanı olarak belirlenip klima santralleri ile galvaniz kanallarla bağlanır. Bu yüzey iki ayrı parça olarak durduğu için Doğu Solarwall yüzeyi ve Batı Solarwall yüzeyi olarak adlandırıldı. Üç (3) modülasyonlu damperler ile klima santraline giren hava kontrol edilmektedir. Kışın Solarwall yüzeyine bağlı damper açık, yazın kuzey cephede bulunan taze hava damperi açıktır. Egsoz havası ile solarwall havasının karışımını karışım damperi ayarlamaktadır. Güneş enerjisinden kazanılan enerjiyi hesaplamak için önce dışarıdan alınan taze hava debisi hesaplandı. Yolcu sayısı giden katında bulunan yolcu giriş kapılarının sayısına göre belirlendi. Saat başına belirlenen yolcu sayısına göre minimum taze hava ihtiyacı bulundu. Bu taze hava ihtiyacı Solarwall sisteminden geçecek olan hava debisine denk olacaktır. Zone 8'in toplam taze hava ihtiyacı 54625 m^3 olarak hesaplanmıştır. Kış aylarında bu taze hava soğutma yükü olarak binaya dönmektedir. Bu soğutma yükünü ne kadar azaltacağımız Retscreen SAH3 program ve Enerji denge çözümleri ile hesaplanmıştır. Retscreen programı ile ilk önce belirlediğimiz Solarwall yüzeyine her ay yatay olarak ne kadar güneş ışığı düştüğü belirlendi. Yararlanılabilecek güneş enerjisi bulunduktan sonra kollektörün ne kadar verimle bu enerjiyi havaya geçirebileceği hesaplandı. Kollektörün verimi birim metrekarede geçen hava debisine ve dış hava rüzgarına bağlıdır. Kollektörlerin verimi % 40 civarında bulunmuştur. Bu sonuç Retscreen'in Solarwall sistemi için çıkardığı verim grafiği ile doğrulanmıştır. Ayrıca solarwall sistemi mahal duvarlarından kaçan ısıyı geri sisteme kazandırarak ek bir enerji kazancı sağlamaktadır. Solarwall sisteminden kazanılan enerji miktarı Retscreen SAH3 programının hesaplamalarına göre yapılmıştır. Hesaplama basit olarak enerji denge korunumu ile karşılaştırılmıştır. Retscreen programının çözümünün direk bu sisteme uygun geliştirildiği ve hesaplarda rüzgarın etkisi alındığı için sonuçların devamınında Retscreen program çözümünü seçtik. Solarwall'dan kazanılan enerjinin yıllık ısıtma ihtiyacı olunan 9 ayın toplamı olarak belirlendi. Bu değer yıllık 393 Mwh'dir. Fakat Mayıs, Eylül, Ekim aylarında kazanılabilecek enerjinin bir bölümüne ihtiyaç olmadığı için toplam kazanılan enerji miktarı 231 Mwh'a düşmüştür. Zone 8'nin yıllık ısıtma ihtiyacının sadece % 12.8 gibi bir değerini Solarwall sisteminden karşılamış olduğumuzu gördük. Bu solarwall sistemi yatırımı içinde kollektörler, işçilik ve diğer giderler (kanal, kablolama) bulunmaktadır. İlk yatırımın % 60'nı kollektörler, % 33'nü isçilik, % 6 diğer giderlerden oluşmaktadır. Toplamda 213.000 Euro olan ilk yatırım maliyetini devletin Enerji destek programları ile % 30 düşürebiliriz. Devlet desteği ile hesaba katarak yapılan yatırım ile geri dönüş süresi yaklaşık 14 yıl bulunmuştur. Bunun en önemli nedeni sistemin % 100 taze hava ile çalışmaması ve kollektörlerinin birim metrekare fiyatının pahalı olmasıdır. Kollektörlerin birim metrekare fiyatı 2013 Türkiye'de fiyatına göre düşünülmüştür. İlerleyen zamanlarda bu birim fiyatın düşmesi sistemin daha cazip bir yatırım olmasını sağlayabilecektir. Enerji verimliliği konusunda binalara enerji sınıfı tanımlanmaktadır. Bina Zone 8'e göre değerlendirildiğinde yıllık metrekareye düşen enerji tüketimi 70 kWh/m^2 year olarak B sınıfında belirlenmiştir. Solarwall sistemi kullanıldıktan sonra bu değer 64.9 kWh/m^2 'e düşmüştür. Bu güneş enerji sistemi düşünülürken sistemin atmosfere yayılacak emisyon miktarında ne kadar azaltma yaratacağı göz önüne alınır. Binanın ısıtması normalde doğalgazlı kazanlardan sağlandığı için metan gazının emisyonu azaltımı hesaplandı ve sonuç olarak 51. 38 ton of CO_2 emisyon düşüşü belirlendi. Hesaplamalar sonucunda sistemin maliyet ve uygulanabilirliği hakkında sonuca varılmıştır. Bu sistem Türkiye için çok yeni bir sistem olup kurulmadan önce binanın ihtiyacları, lokasyonu ve uygulanabilirliği konusunda araştırma yapılmalıdır. Kazanılan ısı enerjisini farklı sistemlerle birlikte kullanarak sistemi daha verimli hale getirmek daha uygun olacaktır.

1. INTRODUCTION

The rapidly growing world causes increases in greenhouse gas emissions in the world. Fossil fuels are consumed to generate electricity or in other mechanical processes. The greenhouses gases are exhausted after burning of fuels. Energy consumption is the most intensive in three main sectors; Industry, transport and the others which include agriculture, services and residential. In developed countries, energy consumption of buildings has increased between 20 % and 40 % [1]. The energy consumption of buildings includes mostly heating and cooling energy. The buildings are heated or cooled by mechanical equipment which is operated by consuming fossil fuels.

The Kyoto Protocol gives a responsibility to reduce CO_2 emission levels to the countries that sign it. This requirement is then reflected as a prerequisite on private companies involved in the energy sector. Solar energy systems utilize solar energy as energy source and are alternatives for companies which are required to utilize sustainable energy sources. These systems aim to reduce the energy needed for heating and cooling. Thus, buildings need less energy which is supplied from boilers or chillers. There are methods available to integrate solar energy into buildings.

This thesis study includes the calculations for conditioning of the departures floor waiting area of Sabiha Gökçen Airport and energy savings as a result of using the chosen solar energy system for pre-heating of the fresh supply air necessary for the area under winter conditions. The airport is located in İstanbul and the calculations were made according to the climate conditions of the city.

2. LITERATURE REVIEW

2.1 Solar Energy Systems

In buildings, solar energy is utilized for different purposes, such as:

- Domestic water heating (DWH)
- Generating electricity
- Cooling
- Heating

Solar energy is most frequently used for domestic water heating purposes where it provides a higher efficiency than other alternatives with respect to supply/demand rates.

Domestic hot water consumption depends on people's habits and geographical conditions. The users can adjust the final temperature by using tap water. The thermal energy, which is needed to heat water, is supplied from solar collectors at different times of day. Absorbed solar energy is stored in a tank and whenever people need hot water, it provides. [2]

Supplied hot water temperature values are adjusted by thermocouples and taps. The desirable temperature is 60 $^{\circ}$C; however the temperature is increased to over 60 $^{\circ}$C for two hours every day in order to prevent Legionnaires' disease. This system has a very simple schematic as shown in Figure 2.1. The DWH solar collectors are easily integrated on the roof of buildings and therefore the most preferred systems in Turkey [2].

Hot fluid is produced from solar energy with solar collectors which are used to drive thermal chiller in absorption chillers. The cooling system generally uses lithium bromide - water solution.

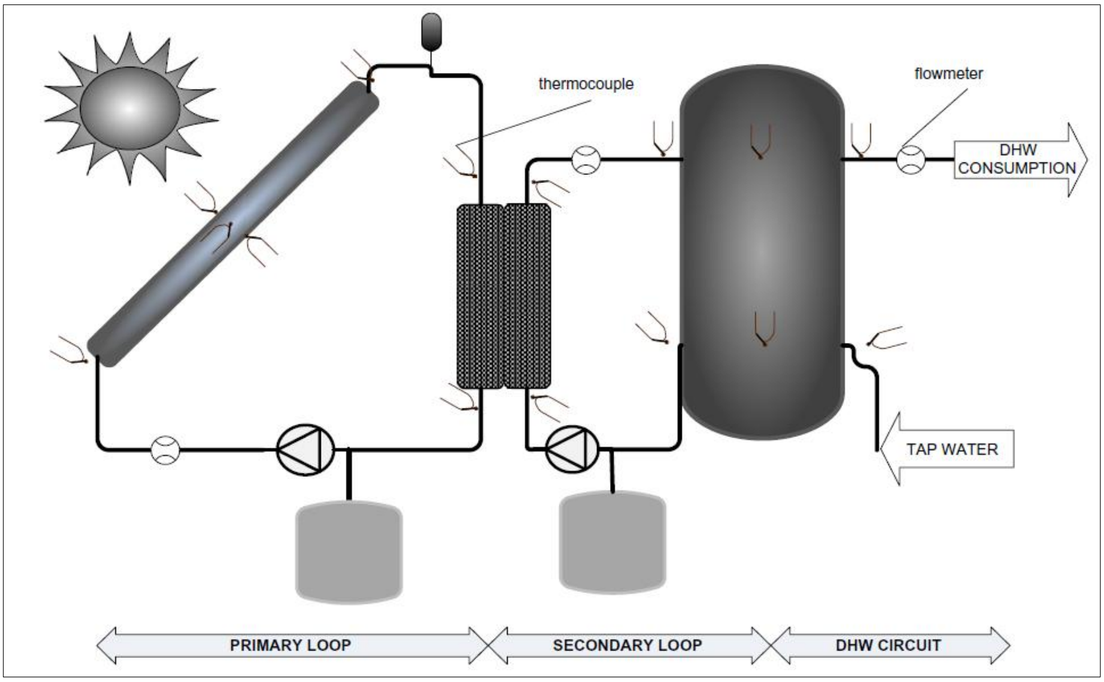

Figure 2.1: Solar Thermal system for DWH [1].

There are three thermal transport circuits; one of them needs hot water supply from solar collectors through refrigerant vapor generators. Around 80 °C of temperature is enough to generate chiller which is easily produced by solar collectors [3]: see solar absorption system Figure 2.2 .

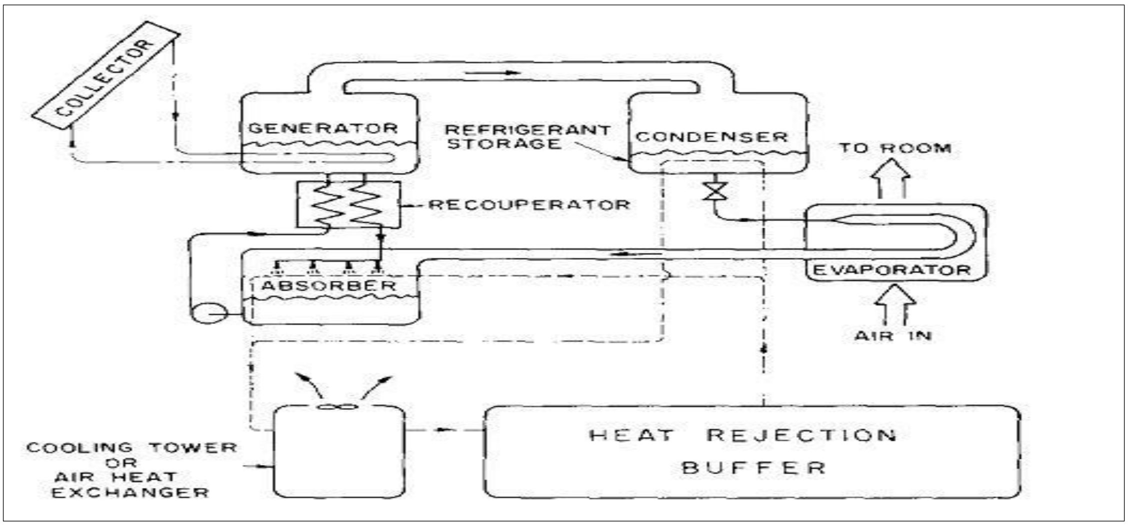

Figure 2.2: Solar absorption system [4].

Photovoltaic (PV) is the process of converting sunlight directly to electricity. PV technology is improved every year. Nowadays, silicon solar cells' efficiency is around 15 %. This system is easily integrated into the building electricity grid with converters [5]. An example of PV application is shown in Figure 2.3.

Figure 2.3: PV integration in a building [5].

Use of solar energy in PV cells and domestic water heating is widely known; however heating of buildings by solar energy is quite unpopular. When the methods are compared to each other, heating systems have higher efficiency than the others.

2.2 Passive Solar Air Heating

When using solar energy for heating of air two approaches are possible. Active heating refers to the use of mechanical or electrical equipment such as pumps and fans to increase useable heat in a system, whereas passive heating refers to the use of solar energy without employing any active mechanical equipment. Passive heating is generally considered more effective in terms of energy cost, since little or no external energy sources are used to drive the process [6].

Tromble wall is a massive wall which is covered by an exterior glazing with air gap. The massive wall absorbs solar energy through glazing. Some part of solar energy is transferred through conditioned space by conduction. Meanwhile the cold inside air passes through the gap and is heated by the wall, then flows upward due to difference of temperatures [6]. Working principle of the Tromble wall is shown in Figure 2.4.

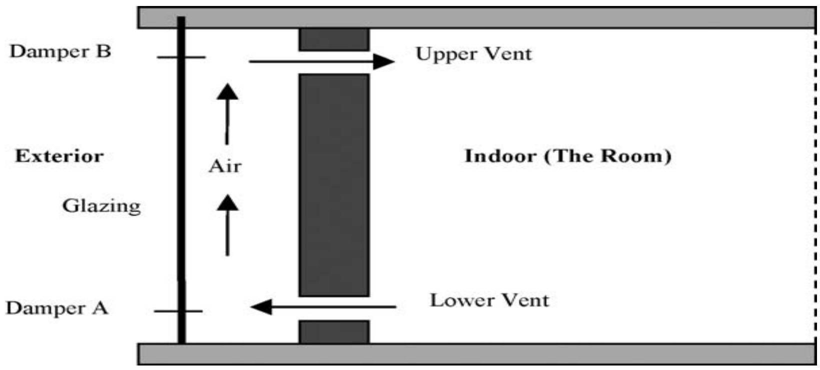

Figure 2.4: Working principle of Tromble wall[6].

Solar Chimney has a purpose of providing air ventilation to buildings. If the chimney is installed on walls, it works in a similar way to Tromble wall. The heated air by solar collectors enters inside of room [6].

Unglazed transpired solar facade is made of metal sheet with small holes that operates as absorber to heat outside air. The system works with fans to supply heated air to intake of air handling units. Conversal Engineering Inc. refers the system as “Solarwall”, which has become the preferred name of this method. Working principle of the Tromble wall is shown in Figure 2.5.

The main advantage of solarwall in comparison to Tromble wall and solar chimney methods is the availability of fresh air that passes through ventilation holes while heat losses via fresh air intake are minimized. Furthermore, it is more easily integrated into the existing air handling units.

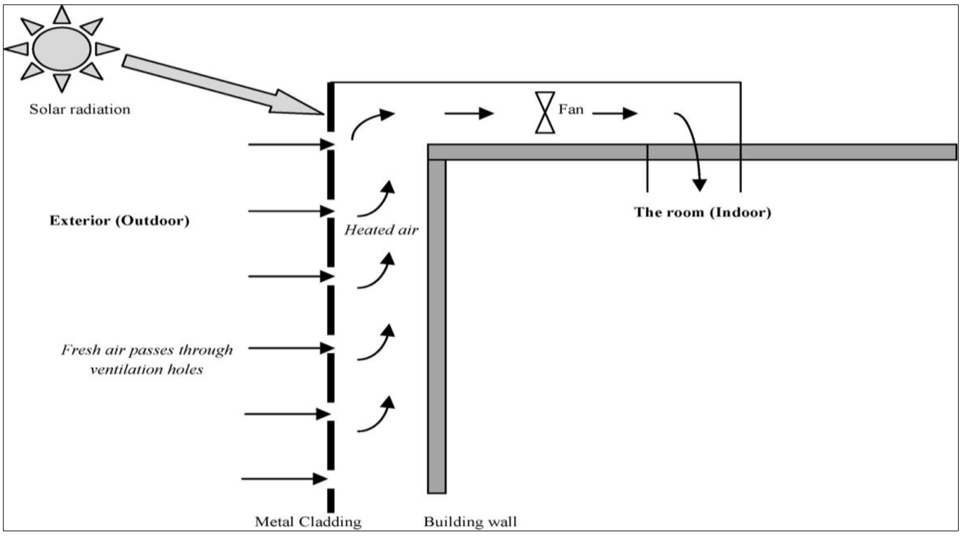

Figure 2.5: Simple view of solarwall [6].

2.3 Solar Wall Technology

The unglazed transpired collector, which is commonly called “Solar wall”, is most frequently used to heat ventilation air in buildings; but it also can be used in some different processes which need heat to run. In late 1970’s, Conversal Engineering started to develop methods to reduce energy consumption in industrial and commercial areas. By the 90's this company invented a new system called Solarwall; a highly efficient solar energy system. It is a proven system for heating and pre-heating air in various applications [7].

Working principle of Solar Wall is shown below in Figure 2.6. Cold ambient air passes through special holes and rises up to the inlet of rooftop, while air is heated by solar wall surface so that the system gains preheated fresh air [8].

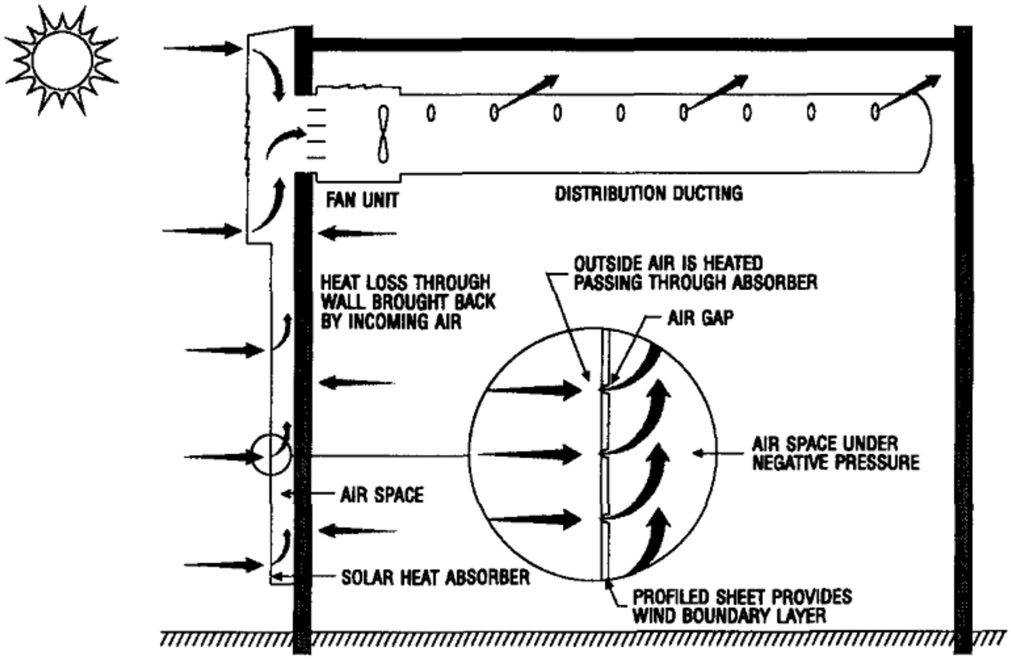

Figure 2.6: Working principles of Solarwall [8].

2.3.1 Panel properties

The metal is perforated with very small holes. The panels have many color types including black, gray, red, blue and green. They are usually composed of overlapping panels of varying lengths and they are installed to give a continuous appearance on the entire wall. To improve structural strength and rigidity, the panels are formed to have a trapeze profile as shown in Figure 2.7.

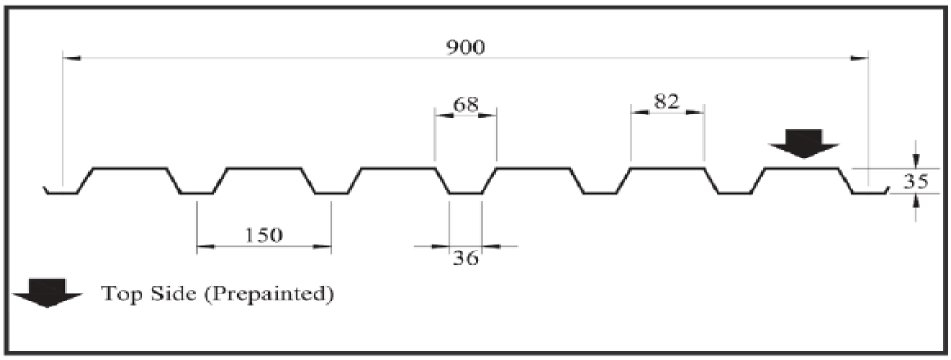

Figure 2.7: Solarwall form [9].

At first, solar walls were produced by using aluminum; however corrosion around small holes occurred after years of usage, which, in turn, prevented air movement through holes. The solar wall panel is found to have no corrosion if galvanized steel is used in panels. For this reason, galvanized steel is more preferred than aluminum. Galvanizing protects from rusting while air moves through holes by drying the moisture in the air. If the solar wall is applied in vertical direction, water flows down the panel surface and small holes keep off water from entering by surface tension. In North America, galvanized steel is preferred because of its low cost. However aluminum is still used in Europe, even though aluminum is more expensive than galvanized steel [9].

The main advantages of the system are high sun-light absorption and specially designed holes. By implementing a special cover on top of the metal, Conversal Engineering has increased the amount of absorption. However, since no information could be obtained regarding this application, only the cover used in solar panels is discussed for exemplary purposes.

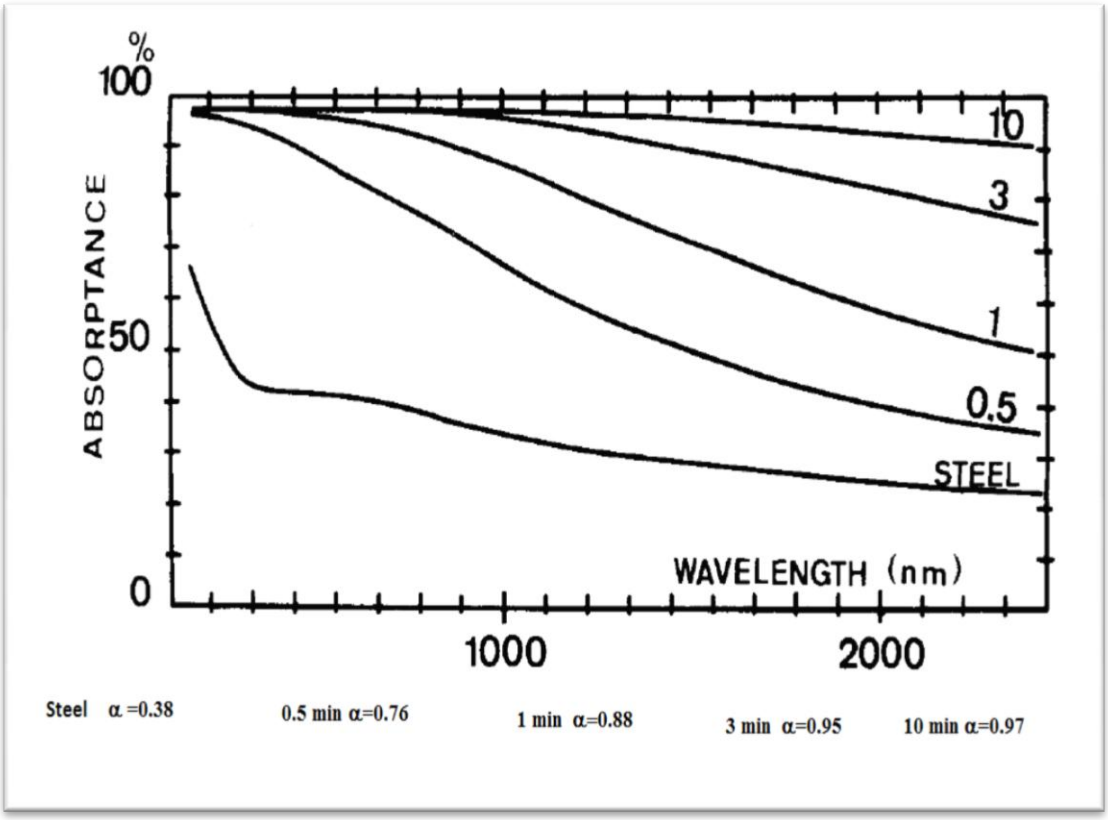

Figure 2.8: Absorptivity ratio as a function of the wavelength for coating at different treatment times [11].

Efficient collectors are constructed by covering copper, aluminum and cast iron surfaces with selective thin film surfaces that are sensitive to sunlight. Chemical covers such as the one shown in Figure 2.8 give the collector the ability to absorb energy with very high efficiency. High absorption ratio of metal surface is reached by applying chemical treatments [10].

Choice of the color on the building facade is up to the contractor. It is important to choose a durable material with no maintenance cost. There are many color types which can be used. When dark colors are chosen, more solar energy can be absorbed since dark color absorbs more solar energy. Color types and absorption rates are shown in Table 2.1.

Table 2.1: Solarwall colors and absorption ratio[9].

Color Name	Absorptivity
Black	0.94
Classic Bronze	0.91
Chocolate Brown	0.9
Hardfort Green	0.9
Med. Bronze	0.89
Boysenberry	0.86
Rocky Grey	0.85
Regal Blue	0.85
Forest Green	0.84

Solar Wall Properties: Solarwall contains aluminum alloys (Mn1Mg0.5) or steel. 1 m^2 of solar wall includes 2500 special designed holes and weighs 2.54 kg. Solar wall's sheet thickness is 1 mm [12]. Below is found the efficiency of the solarwall system in Figure 2.9

- Resistance to corrosion
- Long life (30+ years)
- Non-flammable
- Resistance to bad weather, UV, strong wind
- Low cost price with aluminum alloys, % 95-97 high absorption ratio [12]

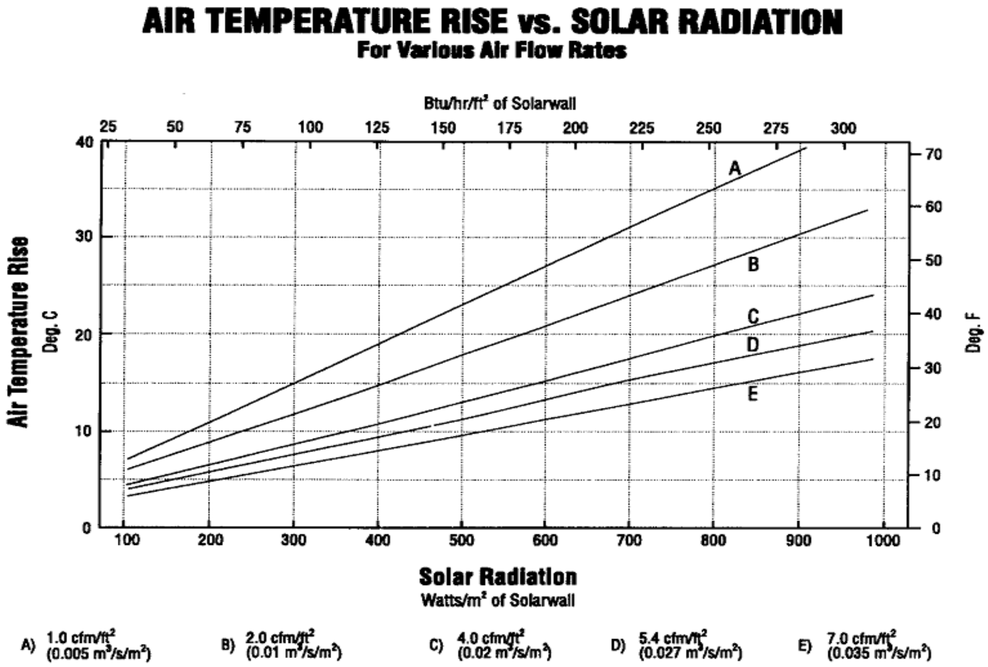

Figure 2.9: Research increment temperature-flow rate using three different wind speed for Solarwall in Canada[8].

2.4 Previous Research on Unglazed Transpired Collector (UTC)

The technology of unglazed transpired collector is investigated by researchers who are sorted below by date.

Kutscher found that a high temperature is obtained when air flows at low rates [13].

Summers investigated the economic aspects of Solarwall usage in commercial, agricultural, industrial and residential areas [14]. The Unglazed Transpired Collector was found to be comparable to electricity as energy source, whereas it was not advantageous against natural gas and fuel-oil.

Hollick studied solar drying in commercial areas [15]. The pay-back time of the system that is used for seed drying in India was estimated as 2 years.

Van Decker studied the energy transfer efficiency in the UTC system [16]. The highest rate of heat transfer occurs through the boundary condition on the surface.

Fleck et. al. simulated the effect of the outside wind on the system [17]. The application of UTC on higher-floor residences was not found to be advantageous as only low fresh air flow rates are required and the area to be heated is smaller.

Delisle and Collins investigated the usage of UTC system with PV modules [18]. As a result, the amount of electricity produced by the PV systems was found to increase when the heat is removed from the panel.

Cordeau ve Barington applied the Solarwall system in a poultry farm [19]. The most important factors that determine the amount of energy produced by the system were found to be solar radiation and wind flow rates.

Athienitis et. al. modelled the usage of UTC system with PV modules and found that the efficiency of the system increases [20].

2.5 Examples of Building Integrated Solar Wall (BISW) Applications

2.5.1 Application of the solarwall on a building facade

Solarwall technology has been tested in many different buildings successfully. Solar wall system is used as cladding of exterior walls in commercial, industrial and residences. For an example, see Figure 2.10 which shows an application in a multi-unit residential complex.

In 1986, Oakville Assembly Plant was covered by Solarwall; this was the first application for Ford Company. In this first application, Ford installed 1858 m^2 of glazed Solarwall in the south facade of the plant as shown in Figure 2.11 . The building was pulling out over 300.000 CFM air while bringing the same amount of fresh air at the same time [21].

Figure 2.10: Multi-unit residential solar air heating project[8].

In 1990, glazed Solarwall was converted to unglazed, perforated, metal Solarwall which had a higher efficiency than the glazed wall. In 1991, ventilation losses were reduced and the company had $100.000 of savings for a year. This result also brought them the achievement of the first plant which succeeded in the ISO 14001 Standard in Canada [21].

Figure 2.11: Oakville Assembly Plant [21].

2.5.2 Building integrated solarwall stage 2 system design (BISW)

Stage 2 is the newly developed BISW concept design as shown in Figure 2.12. The main principle of the concept is based on two stages;

1. Stage: Outside air is heated, passing through the Solarwall absorber.
2. Stage: Pre-heated air is heated for second time as it passes the second Solarwall absorber [22].

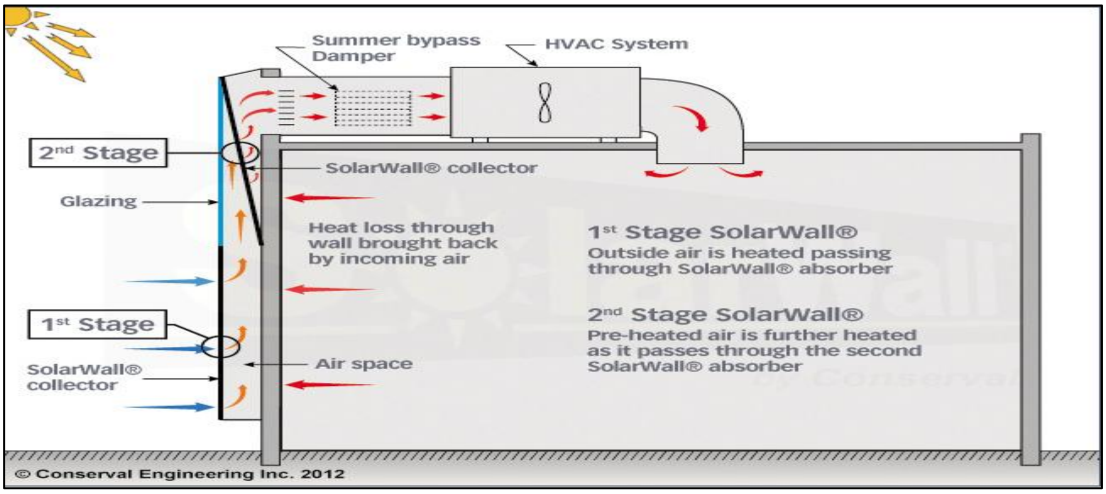

Figure 2.12: Working principle of stage 2[22].

In 2011, Solarwall Stage 2 was installed in buildings of Plattsburgh International Airport which included three hangars and an industrial facility, as shown in Figure 2.13. Solarwall Stage 2 system's area covered a total of 1657 m^2. The air passes across the unglazed Solarwall and it is then heated once as it passes through the glazed portion. Tom Long (Airport Manager) stated that " the buildings now take only 45 minutes to re-heat versus 3 hours before the system was installed" [21].

Figure 2.13: Hangars and facilities at Plattsburgh International Airport [21].

2.5.3 Solarwall and photovoltaic (PV) combined application

The Solarwall/PV system - PV technology combined with Solarwall technology raises the efficiency up to 300 %. The most important benefit of this system is reduction of high temperatures which are produced by the back of PV modules and drops the efficiency of PV modules. The unnecessary heat behind PV module is contributed to heating system of building. Above 25 ^oC temperature drops the electrical output of PV modules [21].

In 2009, Concordia University installed Solarwall together with PV modules. Total installation capacity was 100 kW including 24.5 kW electricity, 75 kW heating system as shown in Figure 2.14. The PV/T system consists of 288 m^2 Solarwall components and 384 PV modules (60 W per module). Supply air flow rate is 25500 m^3/h through the heating system [21].

Figure 2.14: Concordia University Solarwall Application[21].

It is claimed that the combined system improves the efficiency of PV modules by 5 % when compared with the traditional system. The system works as shown in Figure 2.15. PV modules produce heat while generating electricity and produce heat flow through HVAC ducts to be used in heating.

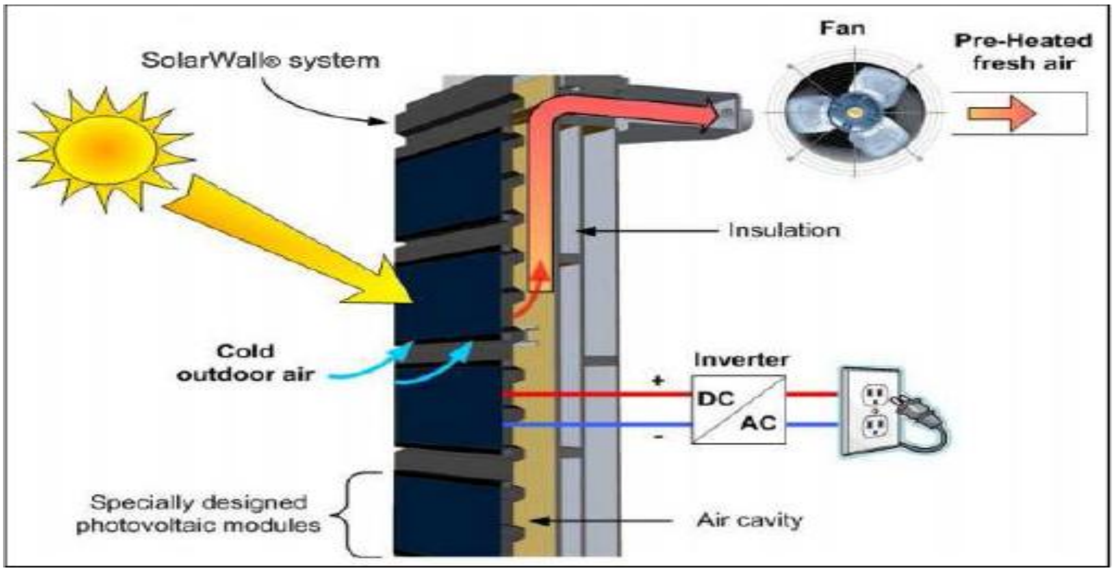

Figure 2.15: Working principles of PV/T[21].

Shandong Jianzu University has carried out an integrative application study on solar energy technology used in a student dormitory and proof-tested the energy conversation efficiency after finishing the building [23]. The dorm's appearance is shown below in Figure 2.16. The construction area is 2300 m^2, and takes up 385 $m^2$of land. The height of the building was 21 m, and it was constructed as brick-concrete [23].

Figure 2.16: The appearance of the building [23].

The location of this project, Jinan City, Shandong Province, is a cold area. Annual heating period is 101 days. During heating days, the outside average temperature is 0.6 Celsius degrees. The dominant wind direction is east-to-north during winter time. The annual average solar radiation quantity is 1744 kJ/m^2 [23]

This technology is newly used in a Chinese building. With this application, Shandong University researchers were able to have some opinions on how the solar wall technology reduces their energy consumptions.

The Shandong University student dorm uses 143 m^2 solar collectors on the wall between windows and cornices on the south facade of building. It can provide 5800 m^3/h of fresh air to 36 rooms that are located in the north facade. Annual energy saving of the system is calculated for 8 months which need heating. It produces 212 GJ energy. According to the study, this energy is not enough to heat all the rooms without any other sources. Working principle of system is shown in Figure 2.17. This study is the first application in China [23].

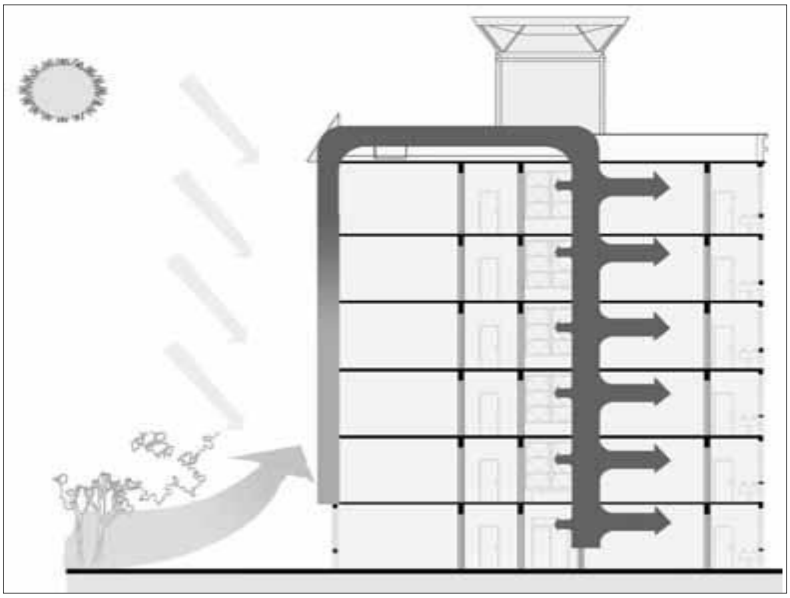

Figure 2.17: The sketch map of system.

There are two significant applications which totally use solar wall energy to supply heating systems in Turkey. The applications are used in CRH and Pim-Sa facilities. These systems were integrated to their heating systems by Teknosolar A.S. CRH facility which produces automotive parts to their customers, located in Gebze-Kocaeli [24]. The factory has 18.000 m^2 of production area. Istanbul is located in 41.1 north latitude and 29 longitudes. 780 m^2 solar wall installed by Johnson Control CRH group is given in Figure 2.18 [24].

Figure 2.18: Unglazed transpired collector application in CRH group [24].

3. THE CASE STUDY& METHODOLOGY

This section focuses on supporting the heating system of the Departure floor of Sabiha Gökçen Airport by installation of Solarwall system. The energy performance of Solarwall is calculated, also the new Solarwall technology with respect to reducing energy consumption and greenhouse emissions is discussed. The methodology is as follows:

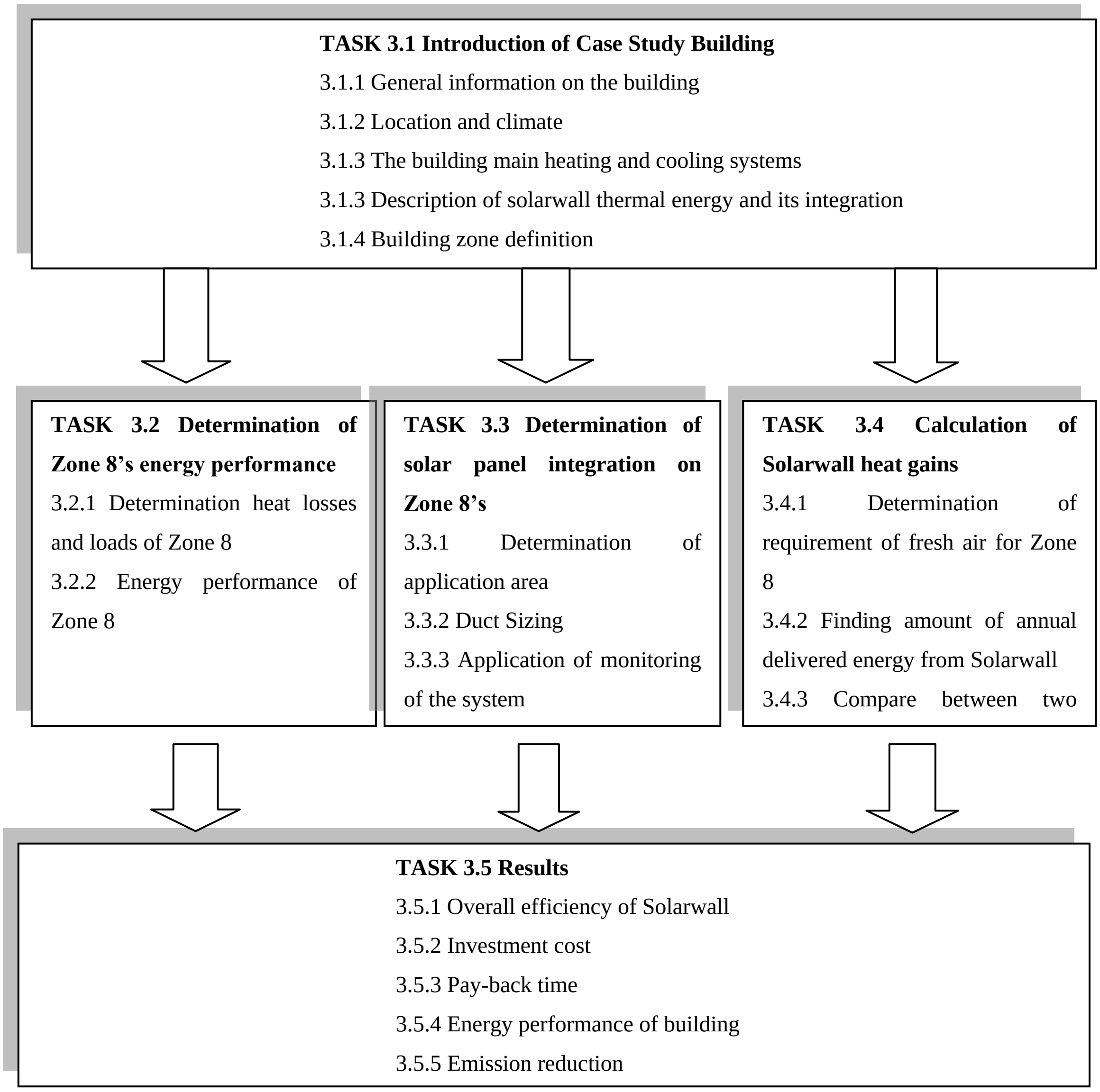

Figure 3.1: Methodology of case study.

3.1 Introduction to The Case Study of Building

3.1.1 General information of the building

The building which was studied - Sabiha Gökçen Airport Terminal - was built by Limak Holding, GMR Infrastructure Limited and Malaysia Airports Holdings Berhad, including the management of the terminal buildings, car park, ground handling, cargo and aircraft refueling operations, the airport hotel and CIP facilities [25].

The new terminal building, an important part of these investments, which will support airport's rapid growth and bring the annual passenger capacity of Istanbul Sabiha Gökçen's to 25 million was built with a modern design with international standards, an environment-friendly structure was opened in 2009 [25].

The features and the services provided by the new terminal building and its complementariness include;

- 112 check-in and 30 self-service check-in kiosks;
- 50 passport counters for incoming and outgoing passengers;
- 5.000 m^2 food court for cafés and restaurants
- 4.500 m^2 Duty Free shopping area is operated by private company
- 3 apron viewing lounges and CIP halls;
- VIP building with terminal connection;
- 400 m^2 conference center;
- Car park with a capacity of about 4,718 vehicles & 72 buses
- Airport hotel with 128 rooms, adjacent to the terminal and with separate entrances at air and ground sides.

Figure 3.2: Appearance of Sabiha Gökçen Airport [25].

Istanbul Sabiha Gökçen International Airport has been the world’s fastest growing airport whose appearance is shown in Figure 3.2. [25]

3.1.2 Location and climate

Sabiha Gökçen Airport Terminal is located in Pendik/Istanbul. İstanbul is located in 41.1 north latitude and 29 longitudes. Climate conditions are given below in Table 3.1 and Figure 3.3.

Table 3.1: The climate condition and radiation in İstanbul [26].

Month	Air Temperature (^oC)	Humidity (%)	Horizontal solar Radiation daily ($kWh/m^2/day$)	Wind speed (m /s)
January	6	73	1.47	5.9
February	5.7	70.4	2.23	6.2
March	7.5	67.5	3.49	5.4
April	11.8	65.2	4.83	4.6
May	16.2	63.2	6.35	4.2
June	20.6	61.9	7.27	4
July	23.1	62.3	7.41	4.6
August	23.3	62.6	6.33	4.9
September	20.5	60.7	4.86	4.7
October	16.5	64.6	2.89	5.6
November	11.5	68.7	1.75	5.5
December	7.6	73.1	1.25	5.9
Average	14.2	66.1	4.2	5.1

Building orientation is very important for the installation of Solarwall. It was found that South facade is the most suitable. According to building orientation, most solar utilizing surface is found to give maximum efficiency. For the installation of Solarwall, best directions are South, South-west and South - east. Orientation of the building is in Figure 3.4.

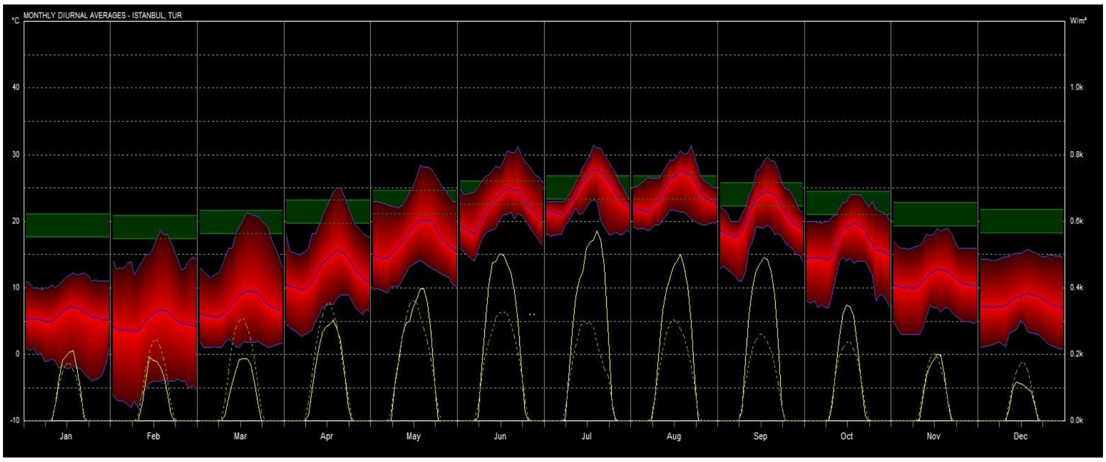

Figure 3.3: Monthly temperature and solar radiation distribution in İstanbul[27].

Figure 3.4: Building orientation [28].

3.1.3 The building main heating and cooling systems

The terminal building is cooled and heated by mechanical equipment which is installed according to the needed heating and cooling energy. There are three steel high efficiency boilers supplying heat and hot water throughout the building. Boiler capacities are 30% higher than calculated capacities. The boilers are operated by consuming natural gas. Fuel-oil is back-up combustion in case natural gas is not fed [29] .

Total heating capacities were calculated as 13250 kW. Contractors took diversity factor as 0.70 and back-up ratio as 0.3.

Installed heating power = 13250 x 0.7 x 1,3 = 12000 kW. Installed boilers are listed below as per contractor's calculation.

1300 kW boiler X 1

3200 kW boiler X 2

4000 kW Trigen supplementary heating[29]

Heat energy is pumped through the Terminal building. Desirable design temperature of heating system is 90-70 °C. Trigeneration system (Trigen) also supplies waste energy in order to be used in heating system. Solar wall system does not perform very well while Trigen generates electricity with supplying waste heat. Our scenario doesn’t include Trigen because of most building has no Trigen system to see the performance of solar wall system.

Cooling system is provided with Chillers which have high coefficient of performance values (COP). There are three water cooled chillers with low operation cost and high efficiency. For transition season, an air cooled chiller is used. Cooling system set design temperature is 6-13 °C.

Total cooling capacities were calculated as 12790 kW. Contractors took diversity factor as 0.70 and back-up ratio as 0.5.

Installed cooling power = 12790 x 0.7 x 1.5 = 13500 kW. Existing chiller’s properties are listed below as per contractor's calculation.

1075 kW air- cooled chiller X 1
3150 kW water-cooled chiller X 2
3000 kW Trigen absorption chiller cooling [29].

3.1.4 Description of solarwall thermal energy and its integration

The best application areas were chosen as Mezzanine floor on South east facade without any shading objects which may prevent the application of the Solarwall. The Solarwall areas are shown as below in Figure 3.5 before application. The fresh air intake already exists on galvanized sheet panels for supplying air through AHU's. Existing fan is enough to supply Solarwall fresh air. Only ducts are mounted from outside to AHU inlets and dampers should be installed to modulate the system.

In our building, solar wall surface is divided into two parts called West solar wall and East solar wall.

In West part solar wall, supply of fresh air flows through 53-54-55-56-57-44 AHU's

In East part solar wall, supply of fresh air flows through 58-59-60-61- 49 AHU's

Figure 3.5: View of Mezzanine floor where Solarwall applied.

3.1.5 Building zone definition

The building includes different unconditioned or conditioned spaces which are heated or cooled by different air handling units. First, spaces of the buildings are defined to specify the Zones which are to be heated by the solar energy system. The zones are defined by using Autodesk Ecotect which is a software program that helps to define borders and specification of Zones. Autodesk Ecotect links 3 D modeling with several analysis functions such as thermal analysis, energy and lightings, solar and cost aspects. This program allows to sketch from simple models to complex ones and gives monthly and yearly energy consumption. The thermal analysis calculation is based on EN 832 standards [27].

The Terminal building which was designed in Ecotect Analysis is shown in Figure 3.6.

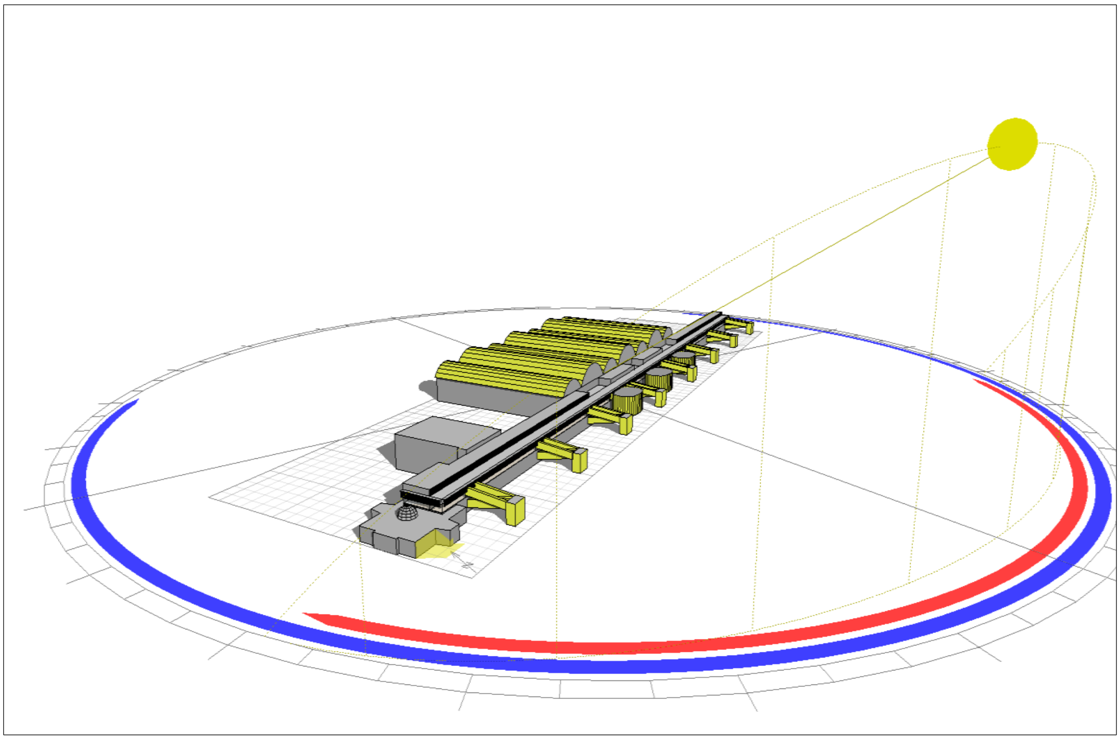

Figure 3.6: 3D model of building by Ecotect Analysis[27].

In order to calculate heat loads and heat losses, "Zone Settings" interface was used. Climate values which depend on the location are imported into Ecotect Analysis. Zone's desirable winter and summer temperatures are entered on the interface of thermostat range [27].

Subsequently, thermal zones were defined for our purpose. Our study was based on heating of Departure Waiting Saloons. Many passengers wait for their flight at the waiting saloons till flight staff starts to confirm their flight tickets. Comfortable place is so important for passenger's satisfaction. Therefore heating and cooling of passengers waiting saloons need more energy than other areas due to the requirement of holding the temperature on a comfortable level. Firstly, Departure waiting saloons are defined in Ecotect Analysis and sixteen saloons are represented as Zone 8 whose properties are listed below.

Zone: Zone 8

Floor Area: 5836 m^2

Volume: 44330 m^3

Our study was based on Zone 8 energy performance and installation of the Solarwall to reduce heat losses in Zone 8. Performance of Solarwall application will be discussed in the section of Zone 8 which is shown Figure 3.7.

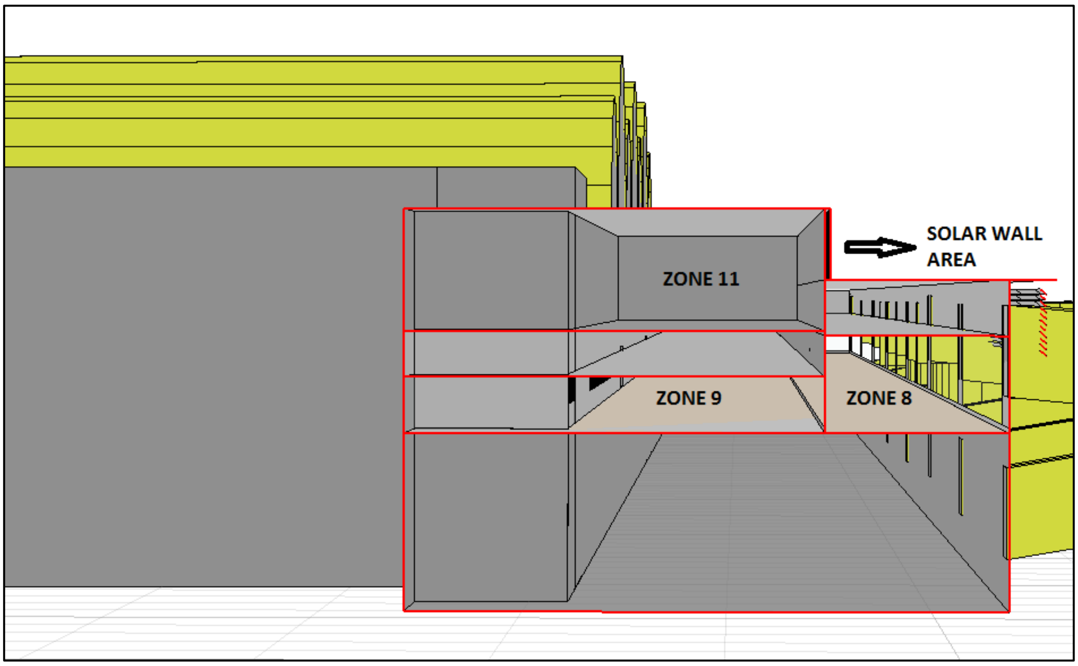

Figure 3.7: Zone Definition of Departure Floor [27].

The average annual lowest and highest temperature of the location helps to determine the energy performance of Zone 8, and is given below.

Winter Min. Temperature = - 3^{o}C

Summer Max. Temperature (dry bulb) = 33^{o}C

Summer Max. Temperature (wet bulb) = 24^{o}C

Zone 8 thermostat range is specified on the terminal project as referred in ASHRAE standards [29]

Winter Interior Zone Design;

Passenger waiting saloons 20^{o}C

Summer Interior Zone Design;

Passenger waiting saloons 25^{o}C

3.2 Determination of Zone 8's Energy Performance

3.2.1 Determination of heat losses and loads of zone 8

First, required heating and cooling energy is determined to see the efficiency of solar energy system with respect to reduction of energy consumption. Determination of heat losses and loads shows how much energy is needed to reach comfortable levels in conditioned spaces. Heat losses and loads included in some parameters are mentioned in this task. All values of heat losses and loads are summed up and help to determine energy performance of Zone 8.

First, heat removed from people's bodies cause inside air to heat up. In order to define the air which is needed to be cooled, heat loads are calculated according to population and types of activities. People produce both sensible heat and latent heat. Therefore chosen activity includes the latent and sensible heat as given in Table 4.1

$$Q_{\text{total sensible heat}} = \text{Population x Sensible heat per person} \quad \textbf{(3.1)}$$

$$Q_{\text{total latent heat}} = \text{Population x Latent heat per person} \quad \textbf{(3.2)}$$

Population is based on the number of gates, which are 16. All planes were assumed as Boeing 737-800 and Boeing 737-400. Each plane has on average 180 passenger capacity. The case where every plane is full and all gates are opened is highly unlikely. That's why; population was multiplied with a diversity factor which is assumed as %80.

Zone 8 (Departure waiting Saloons) population per hour = 180x16x0.80=2300 people

The main activity of people was chosen as sitting from Table A.1 which shows that total heat gain 115 W consists of 70 W sensible heats and 45 W latent heats per person.

$$Q_{\text{total sensible heat}} = 2300 \text{ x } 70 \text{ kW} = 161000 \text{ W} = 161 \text{ kW}$$

$$Q_{\text{total latent heat}} = 2300 \text{ x } 45 \text{ W} = 103500 \text{ W} = 103.5 \text{ kW}$$

The other main heat load is lightings which produce only sensible heat and equipment which, in addition to sensible heat, also produce latent heat depending on the purpose of their usage. The values of lightings heat load per m^2 are chosen in Table A.2 and depend on different occupied spaces [30].

$$Q_{lightning} = \text{Heat load per } m^2 \text{ x Zone area} \quad \textbf{(3.3)}$$

$Q_{lightning}$ is total heat load in Zone 8 due to lightings. Zone area represent as Zone 8 floor area (5836 m^2)

$$Q_{lightning} = 16 \ \frac{W}{m^2} \text{ x } 5836 \ m^2 = 93376 \ W$$

Equipment heat load value is chosen as shown in Table A.3.

$$Q_{equipment} = \ Q_{heat} \ F_{uf} \ \ F_{lf} \quad \textbf{(3.4)}$$

Where Q_{heat} is radiant heat from equipment as shown in Table 4.3, F_{uf} is utilization factor of equipment representing the frequency of handling. F_{lf} is load factor of equipment. Factors are assumed as given below [30];

Equipment utilization factor (F_{uf}) = 0.5

Equipment load factor (F_{lf}) = 0.8

In Departure passenger waiting saloons, each gate has a computer, a monitor and a card reader. There are 16 gates in the defined Zone and additionally 8 monitors in different waiting areas.

$$Q_{equipment} = \ 78560 \text{ W x } 0.5 \text{ x } 0.8 = 31424 \text{ W}$$

The occupied space needs fresh air which is exchanged with polluted air. When the outside temperature is colder than inside temperature, fresh air of intake should be heated. More population and activities cause pollution of inside air. Air exchange rate per person changes with each occupied place, as shown in Table A.4.

According to ANSI/ASHRAE 62-1999, acceptable inside air quality is defined.

$$Q_{vent,sen} = m \text{ x } \rho \text{ x } C_p \text{ x } (T_i - T_o) \quad \textbf{(3.5)}$$

$Q_{vent,sen}$ represents sensible heat losses due of ventilation (kW), m is air flow rate that is supplied through the conditioned space (m^3/s), ρ is the air density that is assumed to be 1.223 kg/m^3. C_p is the specific heat of air which is equal to 1.005 kJ/kg ^oC

The heat losses of ventilation significantly increase energy consumption of conditioned spaces. Unglazed transpired collectors reduce heat losses due to ventilation by pre-heating outside air.

T_i is inside desirable temperature and T_o is outside air temperature.

$$Q_{vent,lat} = mx\rho xh_{fg}x\Delta W \quad \textbf{(3.6)}$$

Where, $Q_{vent,lat}$ is latent heat load because of ventilation, h_{fg} (J/kg) is latent heat of water vapor at suitable temperature which is assumed to be equal to $2.54x10^6$. ΔW (kg/kg) is difference between specific humidity of inside air and specific humidity of outside air [31].

Acceptable flow rate is chosen as shown in Table A.4 with defined conditioned space. If the amount of occupants are known, total flow rate which is needed, is calculated easily.

$$\dot{m} = \text{population x air flow rate per person} \quad \textbf{(3.7)}$$

Infiltration air increases heat losses of buildings in winter.

$$Q_i = S \text{ x } a \text{ x } l \text{ x } R \text{ x } H \text{ x } \Delta T \text{ x } Z_e \quad \textbf{(3.8)}$$

Q_i ; Infiltration heat losses (kcal/h)

a ; Infiltration coefficient (m^3/m h)

l ; Opening distance for windows and doors (m)

R; Space air permeability

ΔT; Difference outside and inside temperature (^oC)

Z_e ; Corner spans effect coefficient

There is no connection between unconditioned spaces and Zone 8, that's why opening distance (l) for windows and doors are assumed to be equal to zero. Therefore the values of infiltration heat losses are negligible.

Heat load from windows by radiation is the one of the heating effects in buildings. Direction and size of windows should be known to find peak heating value of year. After 3D models of buildings in Ecotect Analysis are sketched, heat gain is calculated according to the peak radiation time findings. Peak radiation time values are given in Table A.5. Heat gain by radiation can be reduced by shading sun light. This is described by windows shade factor, K, and is chosen as shown in Table A.6. The area of southwest windows is larger than the other direction's windows area, and is shown in Figure 3.8 . In fact, peak load time is determined as 16:00, when radiation load has its peak on South west.

$$Q_{RN} = F \text{ x } Q_i \text{ x } K \tag{3.9}$$

F (m^2) is the area of windows and Q_i (W) is the heat value of windows in that direction.

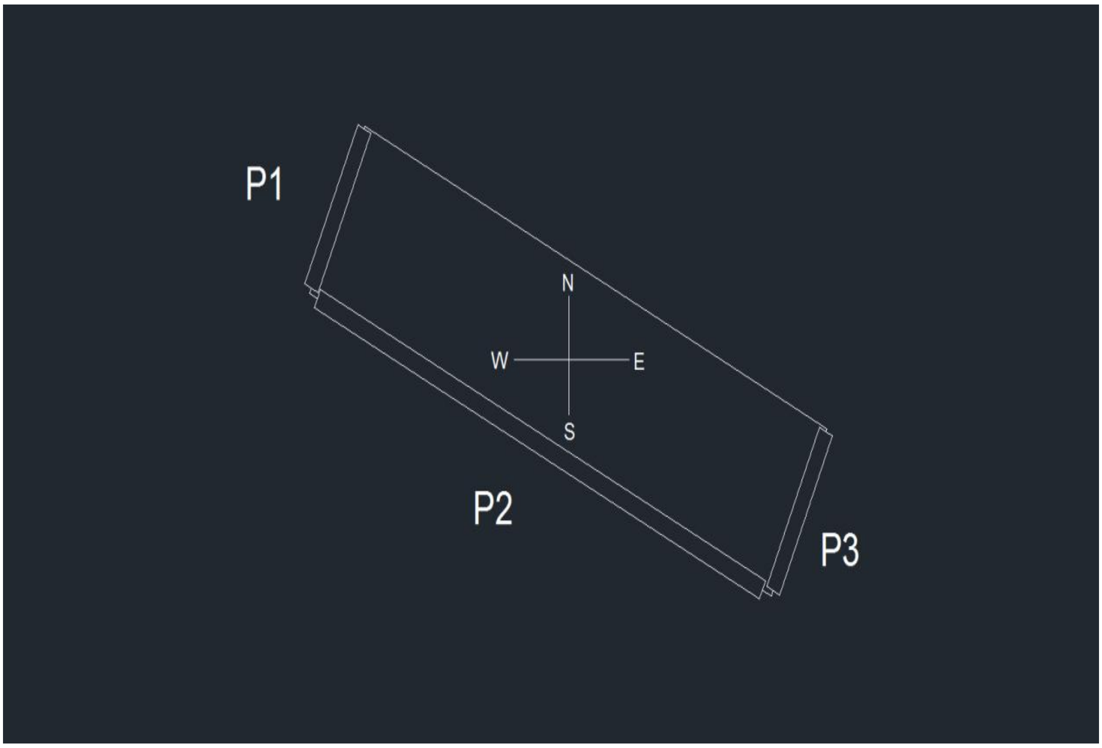

Figure 3.8: Windows area directions on Departure floor.

Lastly, the building is covered with materials to protect spaces. The materials are between outside air and inside air so that energy transfer never stops between outside and inside by conduction. Amount of transferred energy depends on heat resistance of materials that are installed on the building. Finding heat transfer by conduction in windows, walls and roofs are found by using the same equations listed below. Heat transfer direction is defined as seen in Table A.7. Thermal conductivity values of walls, windows and the roof are given in Table B.11-12-13-14-15 in the Appendix according to material properties entered on the interface of Ecotect software.

$$Q_{roof} = U_{value} \text{ x Fx } \Delta t_{equivalent} \quad \textbf{(3.10)}$$

$$Q_{wall} = U_{value} \text{ x Fx } \Delta t_{equivalent} \quad \textbf{(3.11)}$$

$$Q_{windows} = U_{value} \text{ x Fx } \Delta t \quad \textbf{(3.12)}$$

Where; U_{value} gives us thermal conductivity (W/m^2K) that changes with material properties. Each material has a specific thermal conductivity (W/mK), λ. If the structure consists of different materials. U_{value} of structure will find by using belowed equation 3.13.

$$\frac{1}{\text{U value}} = \frac{1}{\propto_i} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_3}{\lambda_3} + \frac{d_4}{\lambda_4} + \frac{1}{\alpha_o} \quad \textbf{(3.13)}$$

d_{index} is the thickness of materials involving wall, roof or windows. These values and properties of material are entered on the interface of Ecotect Analysis which shows us many specific properties of materials. The properties of materials are shown in Appendix with their thermal conductivities and thicknesses.

F (m^2) represents materials surface area. $\Delta t_{equivalent}$ is chosen from Table A.8 after defining peak time and section of roof.

$\Delta t_{equivalent}$ is the difference between inside temperature and outside temperature in windows heat losses. When wall heat losses are calculated, the values of $\Delta t_{equivalent}$ are found as given in Table A. 9

All values of heat losses and loads are defined as energy performance of Zone 8.

3.2.2 Energy performance of zone 8

Ecotect Analysis Program calculates the monthly loads/discomfort values as shown in Table 3.2. The result of energy performance was used to find the efficiency of Solarwall system.

Table 3.2: Energy performance of overall Zone 8.

MONTHLY HEATING/COOLING LOADS

Zone: Zone 8

Operation: Weekdays 00-24, Weekends 00-24.

Thermostat Settings: 20.0 - 25.0 C

Max Heating: 1538.141 kW at 07:00 on 20th February

Max Cooling: 1174.767 kW at 12:00 on 12th September

Month	Heating (kWh)	Cooling (kWh)	Total (kWh)
January	409568.875	0	409568.875
February	424444.281	0	424444.281
March	336228.469	0	336228.469
April	123432.867	626.01	124058.875
May	18669.613	17343.275	36012.887
June	0*	91390.867	91390.867
July	0*	196569.391	196569.391
August	0*	228860.297	228860.297
September	625.927	76079.617	76705.547
October	19584.963	1174.439	20759.402
November	152524.594	670.808	153195.391
December	316677.469	0	316677.469
Total:	1801757.08	612714.66	2414471.68
PER M²	308.709	104.981	413.69
Floor Area:	5838.430 m2		

*Heating systems are not in use during these months according to Istanbul climatic condition

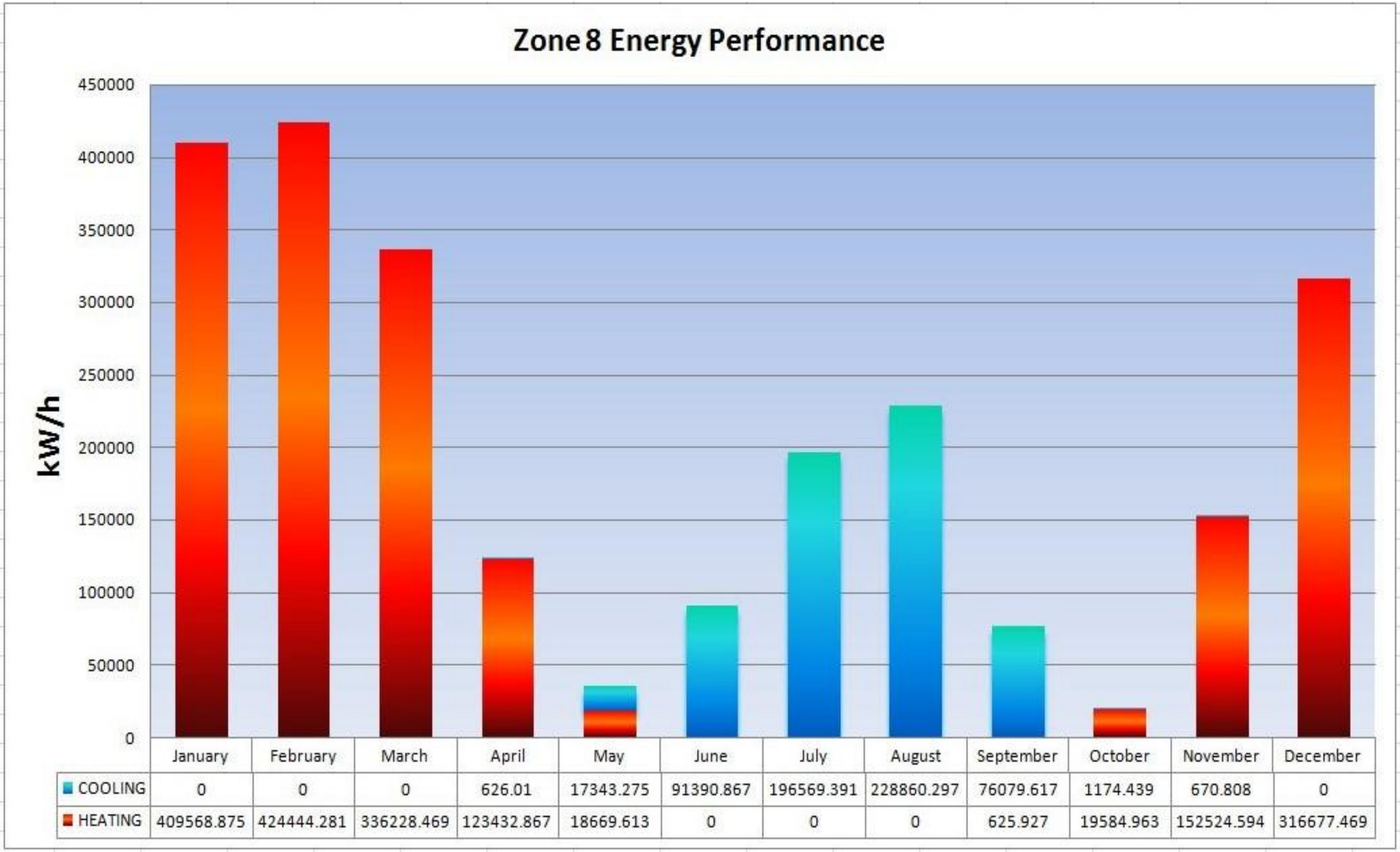

Figure 3.9: Energy performance of Zone 8.

3.3 Determination of Solarwall Integration on Zone 8

3.3.1 Determination of application area

South-west facade was chosen as the most suitable surface for Solarwall application. Solarwall system on the building includes two parts in South-west direction. A total of 1447.5 m^2 areas are suitable for integration of Solarwall system; however this area reduces to 1420 m^2 because of extracting diffuser areas. In the study, this area is divided into two parts that are called as West Part and East Part.

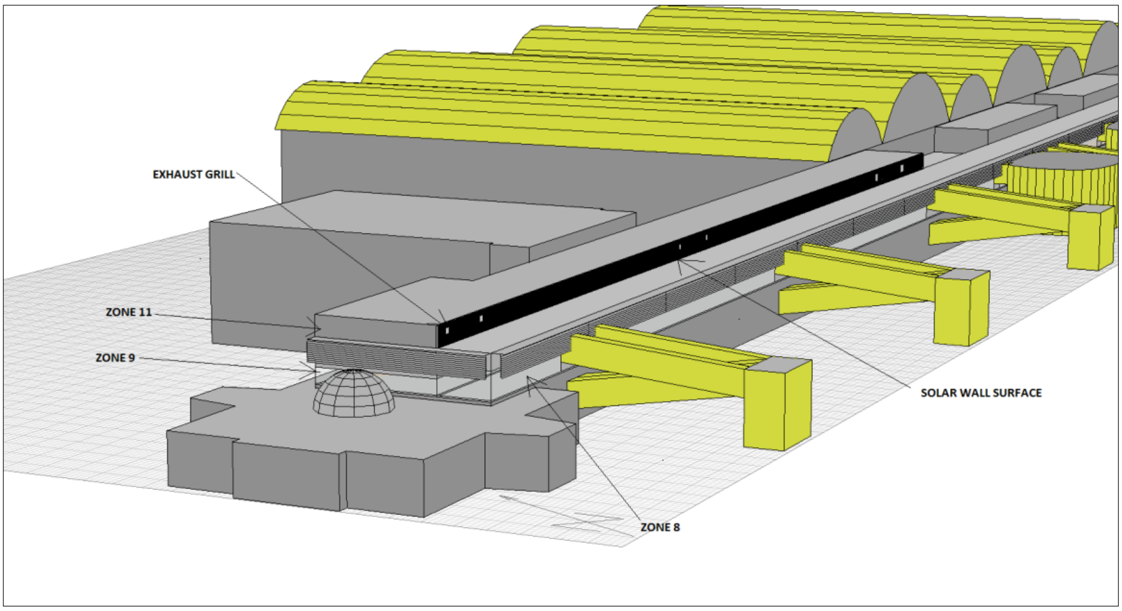

Figure 3.10: West part of the Solarwall [27].

Solarwall applied on Zone 11 facade area is 668,5 m^2 as shown in Figure 3.10, however Air handling unit's (AHU) exhaust grills are not included in the applied surface; actual applied area decreases to 654,8 m^2

Solarwall applied on Zone 12 facade area is 779 m^2 as shown in Figure 3.11, however AHU's exhaust grills are not included in applied surface; actual applied area decreases to 765 m^2.

Solarwall is applied on surface of Zone 11 and Zone 12 where mechanical equipment and storage rooms are located. Pre-heated fresh air from Solarwall flows through AHU's and supplies Zone 8 via galvanized ducts. When calculating actual energy savings, recaptured energy is related with Zone 11.

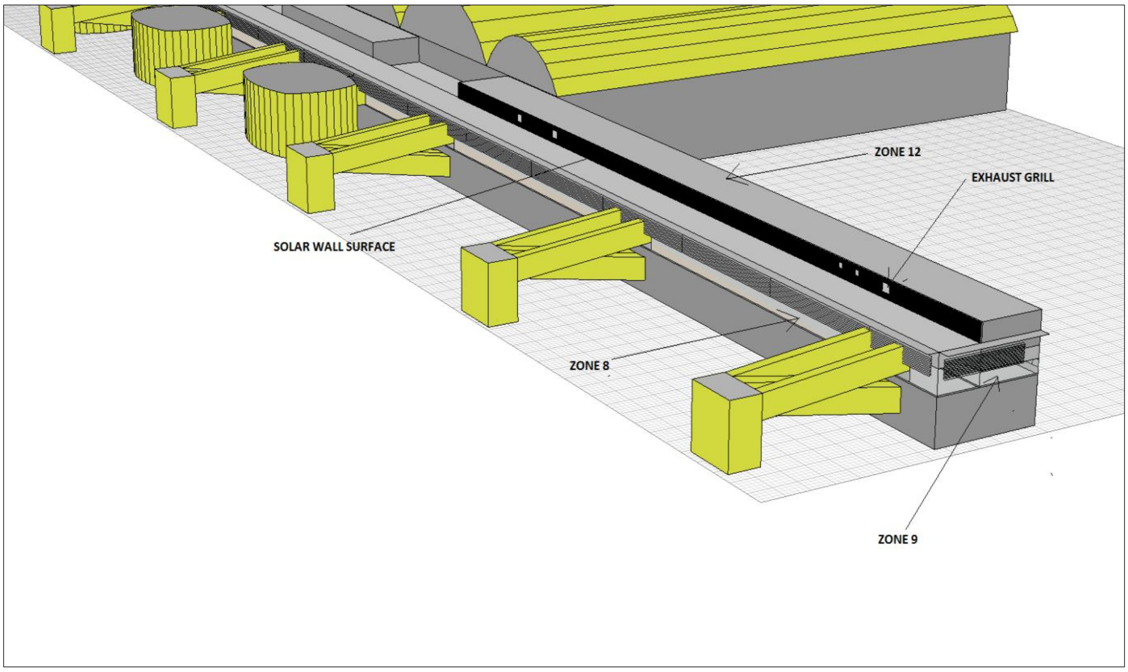

Figure 3.11: East part of Solarwall [27].

3.3.2 Duct sizing

Fresh air heated by Solarwall enters the AHUs via ducts after passing through the fresh air collector. Duct sizes, which depend on cooling capacities, are calculated as given below. First, total heat loads and sensible heat loads should be determined to find sensible heat ratio (SHR).

$$SHR = \frac{Q_{\text{Sensible heat load}}}{Q_{\text{total heat load}}} \tag{3.14}$$

Latent heats which are removed by human activities are extracted from total heat loads to find sensible heat load. By using SHR ratio, the slope of line is determined, which is drawn from inside set temperature to cooling degrees and intersects with parabola of 90 % humidity in psychometric diagram. 90 % humidity means condensation limit in psychometric diagram as shown in Figure 3.12. Intersection point of line and the parabola show the minimum delivered temperature which flows through conditioned spaces.

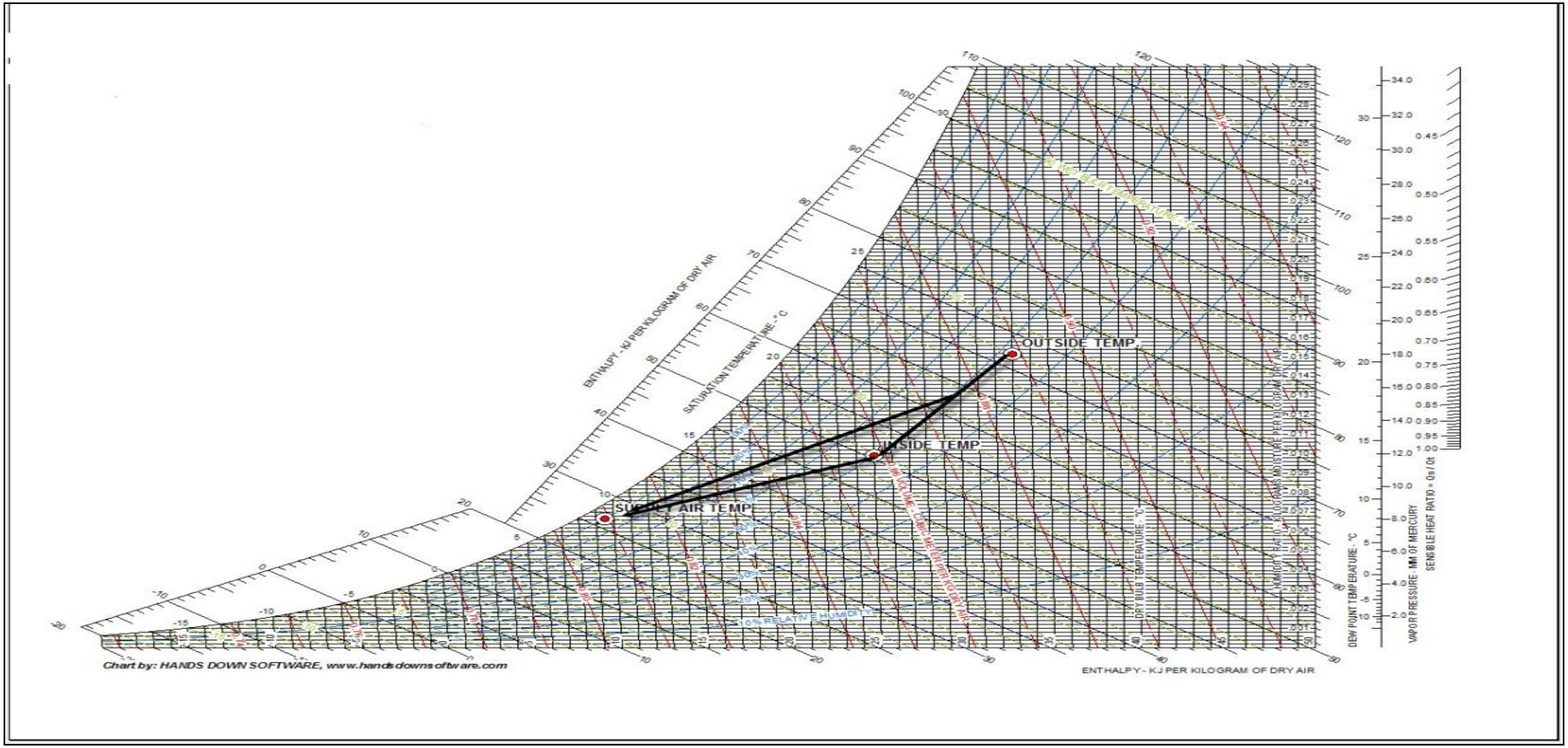

Figure 3.12: Psychometric diagram shows minimum supply air.

$$Q_{sensibleheat} = m x \rho x C_p x \Delta T \quad (3.15)$$

Where m is supply flow air rate (m^3/h), ρ is the air density that is assumed as 1.223 kg/m^3. C_p is the specific heat of air which is equal to 1.005 kJ/kg ^oC. Supply flow rate can be found using the equation above and flow rate of each AHU is calculated.

$$\Delta T = \text{Inside design temperature} - \text{Minimum supply air temperature} \quad (3.16)$$

Duct sizes can be defined by using the below equation 3.17. F (m^2) is duct section area; V (m/s) is velocity of air that provides a comfortable noise level which is determined as shown in Table A.10.

$$Q_{\text{supply main duct}} = F \text{ x } V \quad (3.17)$$

Actual duct size is determined by deriving from duct section area using the below equation. Then the diameter of duct section is converted into a rectangular section size in Table 3.3. Connection of ducts to AHUs is done as seen in Figure 3.13.

$$F = \frac{\pi \text{ x } D^2}{4} \quad (3.18)$$

Table 3.3: Installed ducts size.

DUCTS					
Ahu N	Flow Rate (m^3/h)	F (m^2)	Circle Diameter (m)	Rectangular size (cm)	Average Length (m)
53	9334	0.35	0.66	60 x 60	10
54	9334	0.35	0.66	60 x 60	10
55	8139	0.30	0.62	65 x 50	10
56	8139	0.30	0.62	65 x 50	10
57	8480	0.31	0.63	75 x 45	10
44	8480	0.31	0.63	75 x 45	10
49	8480	0.31	0.63	75 x 45	10
58	8480	0.31	0.63	75 x 45	10
59	7228	0.27	0.58	70 x 40	10
60	8139	0.30	0.62	65 x 50	10
61	21969	0.81	1.02	110 x 80	10

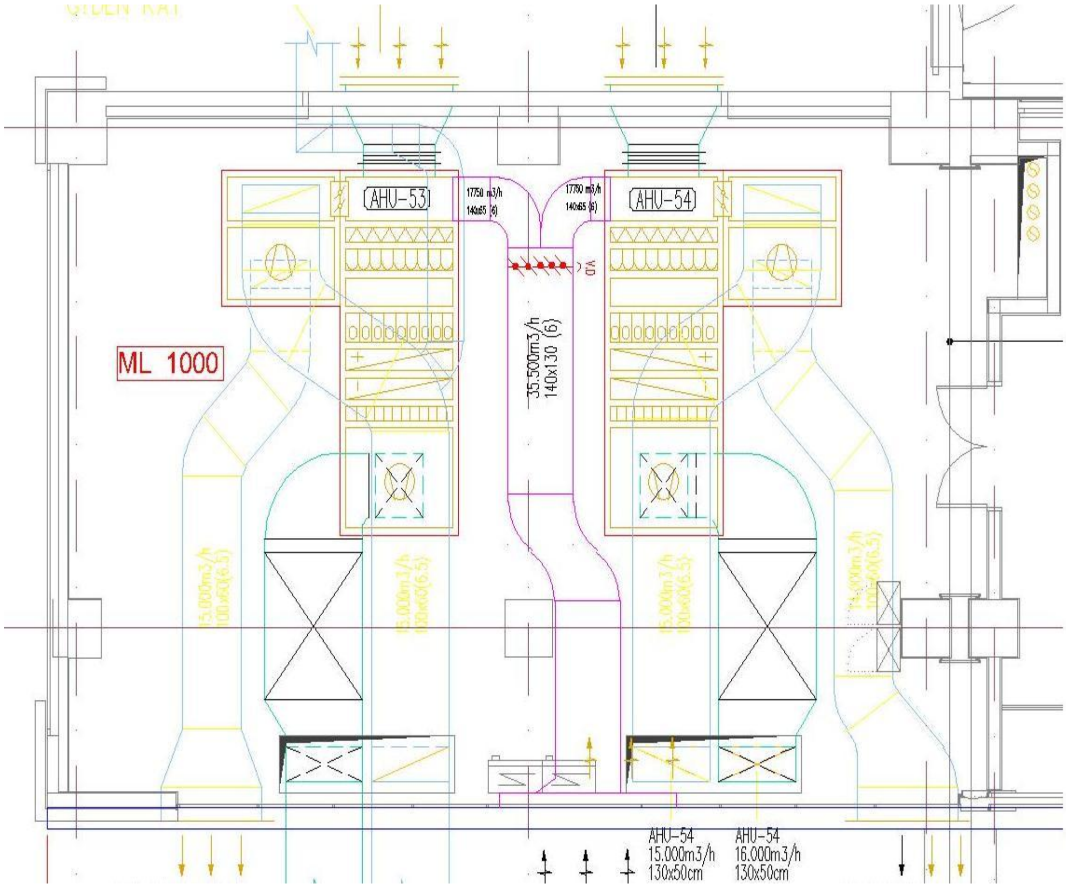

Figure 3.13: Connection of Solarwall ducts to AHU's.

After determining the duct sizes and total flow rate (m^3/h), delivery temperature in winter time is found easily.

$$Q_{\text{heat losses}} = \dot{m} \text{ x } \rho \text{ x } C_p \text{ x } \Delta T \qquad \textbf{(3.19)}$$

where $Q_{\text{heat losses}}$ (kW) is heat losses of Zone 8 in coldest time of year, ρ is the air density that is assumed as 1.223 kg/m^3. C_p is the specific heat of air which is equal to 1.005 kJ/kg ^oC. M is maximum flow rate of air handling units which was found in previous equations.

$$\Delta T = \text{Supply Temperature °C} - \text{Ambient Temperature °C} \qquad \textbf{(3.20)}$$

When every value is entered into the equation, supply temperature is found as 28.7 ^oC for Zone 8.

3.3.3 Application of monitoring system

Most of the common areas are cooled or heated by AHU's system. Server rooms are cooled by Variable Refrigerant Volume (VRV) or split air conditioners. Fan coil unit (FCU) systems are used in almost all offices. There are different systems to cool or heat places as defined.

All AHU's, VRV systems and some FCUs are operated by technician persons using the Building management system (BMS) as shown in Figure 3.14 below. All setting values are checked or changed by operating the BMS.

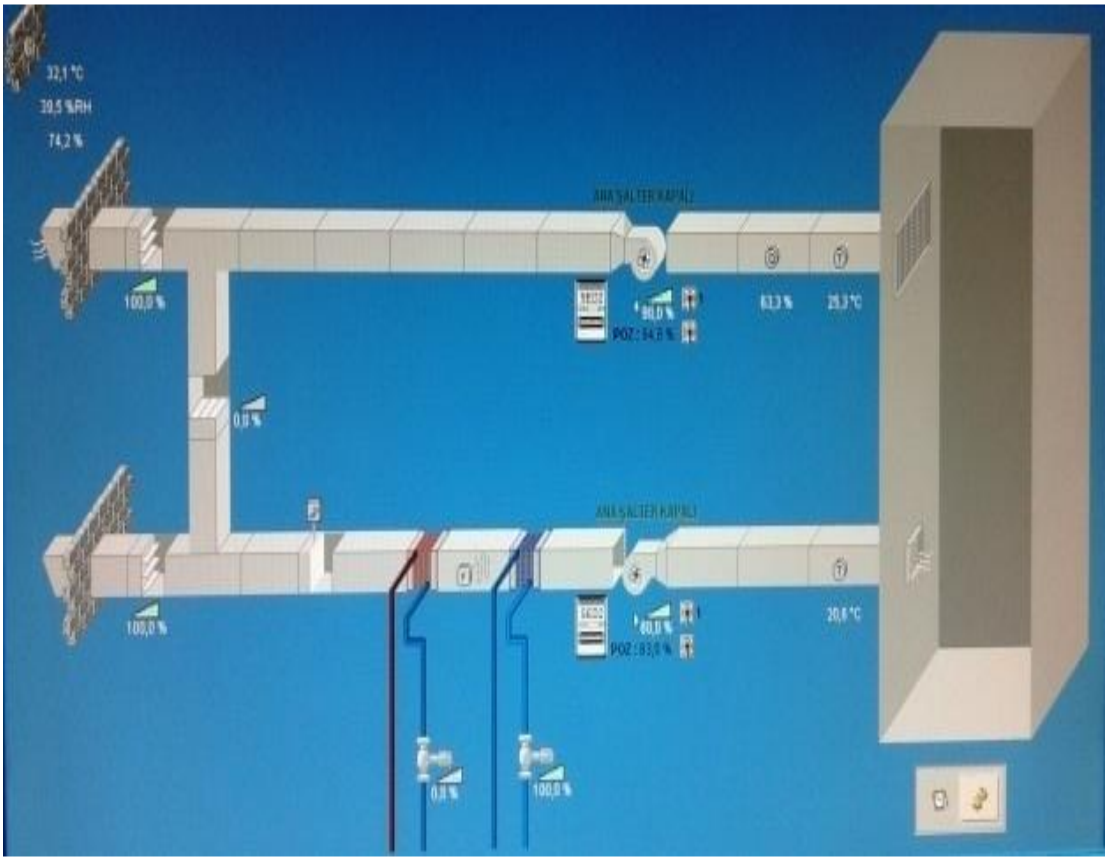

Figure 3.14: AHU 49 operating window without Solarwall system.

After the systems are installed, zone setting values are adjusted as per the requirements of spaces. Technicians adjust some values based on significant requirements. Minimum fresh air ratio is defined as 10 % of total supply air of zones. Operator can change the ratio of fresh air in conditioned air. When air quality is decreased in spaces, system needs fresh air entering from outside so system consumes more energy for heating or cooling outside air.

AHU's system works with fresh air inlet as shown in Figure 3.14. After Solarwall is integrated on the South facade, System will be improved as in Figure 3.15. There are three main dampers which are modulated by BMS and Solarwall automation system (BSRIA) system.

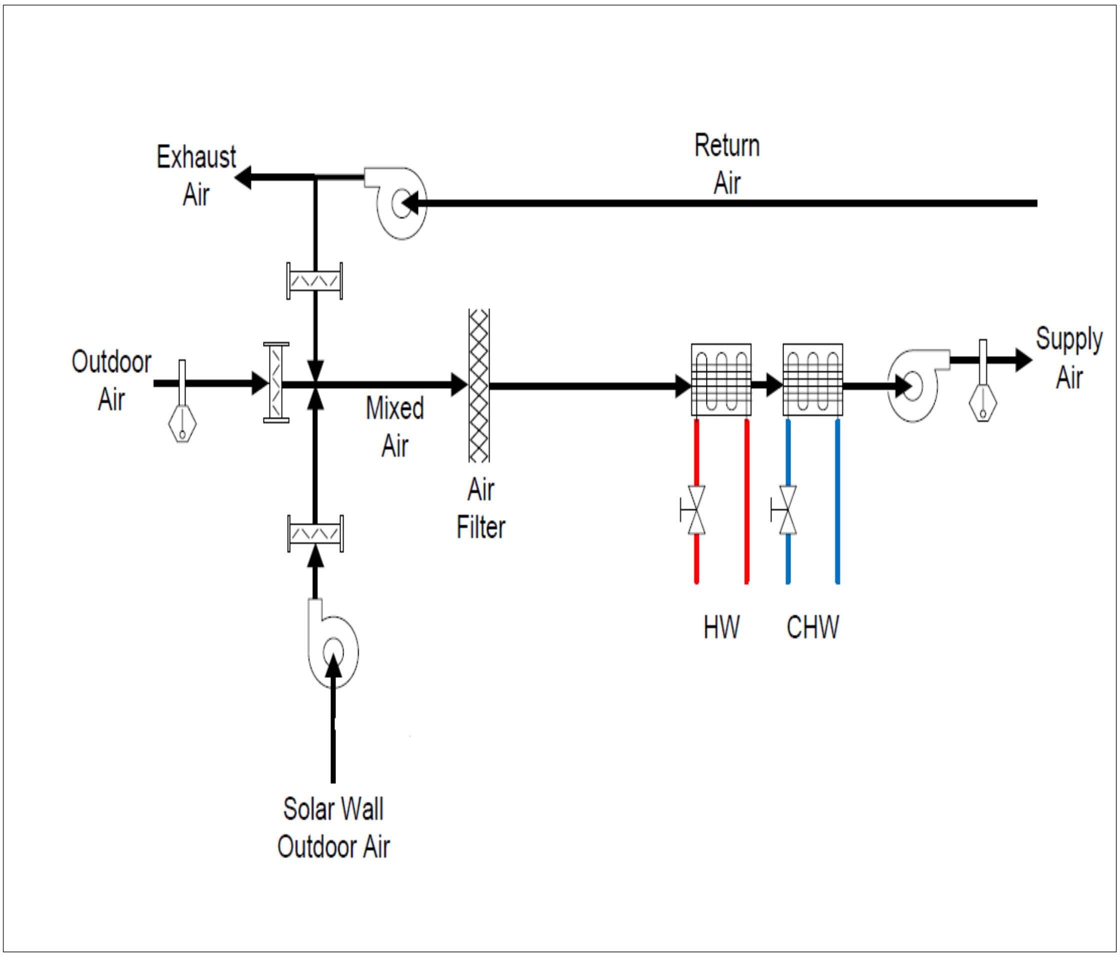

Figure 3.15: AHU’s system with Solarwall [32].

With solar wall integrations, BSRIA monitor is installed in computer of BMS room. Thus operators can monitor Solarwall intake air temperature easily.

Thermocouples are mounted between Solarwall surface and normal wall surface. Thermocouples grid is generated to get more reliable information on Solarwall temperature. Thermocouples are arrayed around inlet with different horizontal and vertical distances. Furthermore, sensors are put in the ducts to modulate the system[33].

For all thermocouples, sensors, damper modules, cables will be laid through the control panel which connects to BSRIA computer in BMS room. Monitoring system display, which can be easily operated by operators, is shown in Figure 3.16.

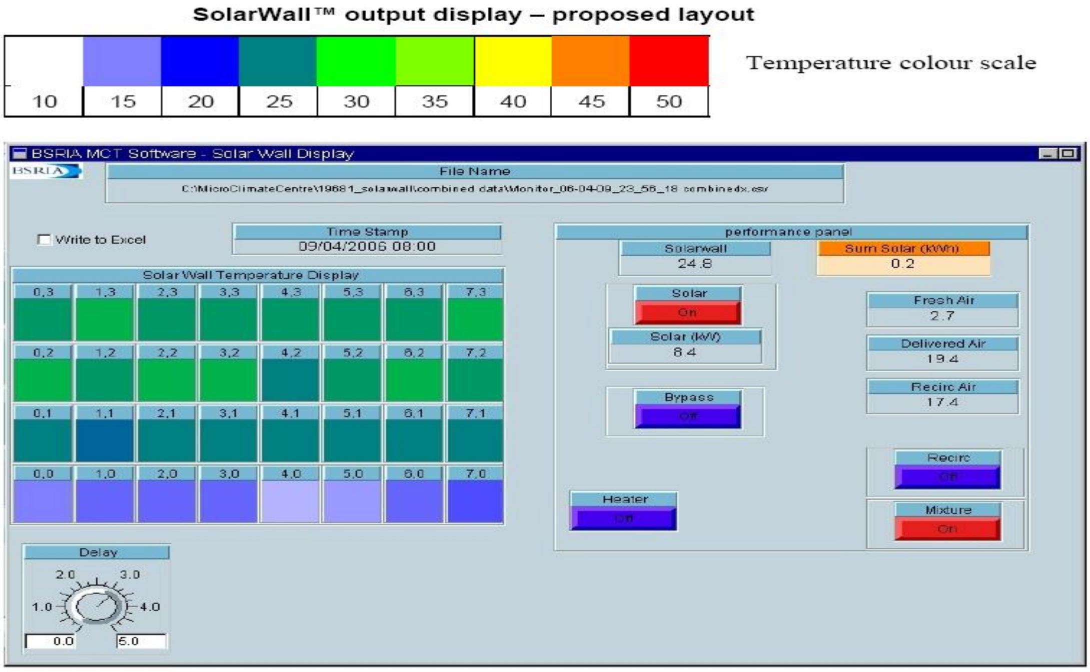

Figure 3.16: BSRIA Solarwall monitor [33].

Scenario Monitor;

- Solar air damper opened fully when Zone 8 temperature is below 20 $^{\circ}$C, outside temperature below 18 $^{\circ}$C and solar wall temperature is more than 20 $^{\circ}$C (low level sensor).
- If internal temperature is above 20 $^{\circ}$C. Recirculated air delivers through internal area however it also depends on rate of air quality and minimum fresh air set value.
- Building internal temperature is below 20 $^{\circ}$C and solar wall temperature is also below 20 $^{\circ}$C. All three dampers are modulated by program.

3.4 Calculation of Solarwall Heat Gains

After calculating energy performance of Zone 8, in this section, Solarwall heat gain is calculated with reference to Retscreen SAH program. Retscreen is an association which provides clean energy softwares. The method of calculations is based on

Retscreen SAH textbook. Therefore, energy balance equations are used for comparing results between its and SAH results.

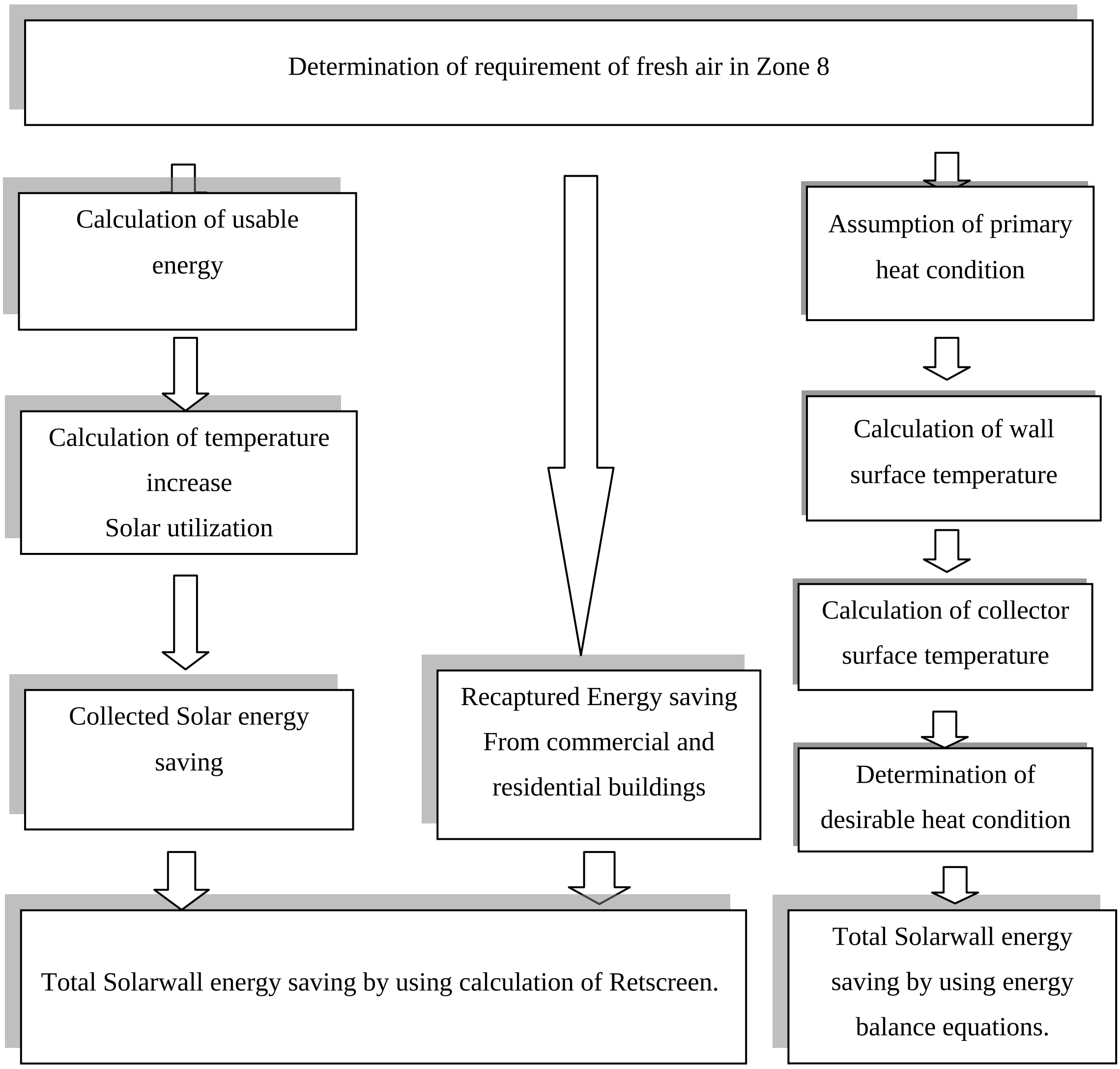

Figure 3.17: Flowchart of Solarwall energy saving calculations.

3.4.1 Determination of fresh air requirements for zone 8

First, required fresh air of Zone 8 is determined to find pre-heated air volume by Solarwall. Amount of fresh air in Zone 8 was determined as 30 m^3/h per person in Table 4.4. Occupancy is 2300 people /h.

$$Qf = 2300 \times 30 = 69000 \text{ m}^3/\text{h}$$

In winter, recirculation of the inside air provides more energy savings because inside air is hotter than outside air; however percent of CO_2 increases as a result of human activities. The minimum amount of fresh air needed is calculated as 69000 m^3/h at peak population time

Between 00:00 and 05:00 time, flight counts are down; the rest of day the departure floor is full.

$$Qs = 69000 \, x \frac{19}{24} = 54625 \frac{m^3}{h}$$

Total area of Zone 8 = 5836 m^2

West part of the Solarwall feeds air to some parts of Zone 8 with defined AHU's,

Width = 9 m , Length = 245.57 m

West part floor area = 9 x 245.57 =2210 m^2 + 811.25m^2 = 3021.25 m^2

East part of the Solarwall feeds air to different areas in Zone 8

Width = 9 m, Length = 222.6 m

East part floor area = 9 x 222.6 = 2003.5 m^2 + 811.25 m^2 = 2814.75 m^2

Required fresh air depends on the intensity of people concerned with the floor area.

Zone 8 has no separated division; therefore all fresh air is supplied from AHU's which are integrated in the Solarwall.

West part of the Solarwall $Q_f = \frac{54625 \frac{m^3}{h} x \, 3021.25 \, m^2}{5836 \, m^2} = 28279 \, m^3/h$

East part of the Solarwall $Q_f = \frac{54625 \frac{m^3}{h} x \, 2814.75 \, m^2}{5836 \, m^2} = 26346 \, m^3/h$

3.4.2 Annual delivered energy from Solarwall

3.4.2.1 Usable incident solar energy calculation

In this task, incident solar energy of defined surface is determined. Each month has different average incident solar energy according to sun position. For each month , i, solar energy which can be used, is represented as $G_{coll,i}$. Solar energy incident through collectors, $G_{tilt,i}$ and the collector area A_{coll}[7].

$$G_{coll,i} = G_{tilt,i} A_{coll} f_{op,i} \qquad \textbf{(3.21)}$$

$G_{tilt,i}$ is derived from defined values of average daily solar radiation on the horizontal surface. Solarwall surface in Ecotect Analysis program also helps us to determine the actual values of $G_{tilt,I}$ that one of the main reason the building is designed by using Ecotect Analysis

$$f_{op,i} = n_{day,i} f_{sys,i} \frac{h_{op,daytime}}{h_{sunlight,i}} \frac{d_{op}}{7} \qquad \textbf{(3.22)}$$

where, $n_{days,i}$, is the number of days in month i, $f_{sys,i}$ is the entered fraction of the month for the system operation, $h_{op,daytime}$ is the number of operation hours while the sunlight strikes Solarwall, $h_{sunlight,\ i}$ is the number of sunlight hours in a day of selected month, d_{op} is the operating day in a week [7].

$h_{sunlight,i}$ depends on the time year and latitude, changing every day. These values can be taken from NASA website, depending on building location. The results of usable incident solar energy are given in Table 3.4 and Table 3.5.

Table 3.4: Usable incident solar energy of West part.

West Part Months	Avaiable Solar Energy kWh/m^2 d	Collector Area m^2	Days d	Fraction	Stored Energy kWh
January	1.21	765	31	1	28695
February	1.119	765	28	1	23968
March	1.299	765	31	1	30805
April	2.437	765	30	1	55929
May	3.472	765	31	1	82338
June	4.514	765	30	0	103596
July	5.044	765	31	0	119618
August	4.256	765	31	0	100931
September	4.001	765	30	1	91822
October	2.101	765	31	1	49825
November	1.199	765	30	1	27517
December	0.708	765	31	1	16790
				Total:	**407692**

Table 3.5: Usable incident solar energy of East part.

East Part Month	Available Solar Energy kWh/m^2 d	Collector Area m^2	Days d	Fraction	Stored Energy kWh
January	1.21	655	31	1	24569
February	1.119	655	28	1	20522
March	1.299	655	31	1	26376
April	2.437	655	30	1	47887
May	3.472	655	31	1	70498
June	4.514	655	30	0	88700
July	5.044	655	31	0	102418
August	4.256	655	31	0	86418
September	4.001	655	30	1	78619
October	2.101	655	31	1	42660
November	1.199	655	30	1	23560
December	0.708	655	31	1	14375
				Total:	**349070**

3.4.2.2 Average collector efficiency

The efficiency of Solarwall depends on many variables among which air flow rate and wind speed are the most important on the surface of collector. A collector efficiency equation is derived from a heat balance on the Solarwall [7].

When $Q_{collector}$ represents air flow rate and v_{wind} is the wind speed, the Efficiency of collector is shown as η

$$\eta = \frac{\alpha}{1 + \frac{\frac{20v'_{wind}}{\dot{Q}_{collector}} + 7}{\dot{Q}_{collector}\ \rho C_p\ (1 - 0.005\dot{Q}_{collector})}} \qquad \textbf{(3.23)}$$

α is the solar absorptive of collector which change with its color. ρ is the air density assumed as 1.223 kg/m^3. C_p is the specific heat of air which is equal to 1.005 kJ/kg ^oC

A simple formula shows monthly average wind speed with no shading

$$v'_{wind} = 0.35 v_{wind} \quad \textbf{(3.24)}$$

$$\dot{Q}_{collector} = \frac{\text{Total Supply air flow rate}}{\text{Applied solar wall area}} \quad \textbf{(3.25)}$$

Efficiency of West part and East part of solarwall are given in Table 3.6 and Table 3.7.

Table 3.6: Efficiency of collectors in West part.

West Part Month	$Q_{collector}$ m3/s	Wind Speed m/s	$\mathbf{v'_{wind}}$ m/s	Solar Absorptive	Efficiency %
January	7.99	5.9	2.065	0.94	41.03
February	7.99	6.2	2.17	0.94	40.54
March	7.99	5.4	1.89	0.94	41.88
April	7.99	4.6	1.61	0.94	43.32
May	7.99	4.2	1.47	0.94	44.07
June	7.99	4	1.4	0.94	0
July	7.99	4.6	1.61	0.94	0
August	7.99	4.9	1.715	0.94	0
September	7.99	4.7	1.645	0.94	43.13
October	7.99	5.6	1.96	0.94	41.54
November	7.99	5.5	1.925	0.94	41.71
December	7.99	5.9	2.065	0.94	41.03

Efficiency of West part an East part was found, but these values are low. When these results are compared with Retscreen results (Figure 3.18), it shows that these values are normal.

West part collectors flow rate 28279/765 = 39.96 $m^3/h\ m^2$

East part collectors flow rate 26346/665 = 40.22 $m^3/h\ m^2$

Table 3.7: Efficiency of collectors in West part.

East Part	Q collector	Wind Speed	v'_{wind}	Solar Absorptive	Efficiency
MONTH	m3/s	m/s	m/s		%
January	7.32	5.9	2.065	0.94	38.22
February	7.32	6.2	2.17	0.94	37.71
March	7.32	5.4	1.89	0.94	39.10
April	7.32	4.6	1.61	0.94	40.59
May	7.32	4.2	1.47	0.94	41.38
June	7.32	4	1.4	0.94	0
July	7.32	4.6	1.61	0.94	0
August	7.32	4.9	1.715	0.94	0
September	7.32	4.7	1.645	0.94	40.40
October	7.32	5.6	1.96	0.94	38.74
November	7.32	5.5	1.925	0.94	38.92
December	7.32	5.9	2.065	0.94	38.22

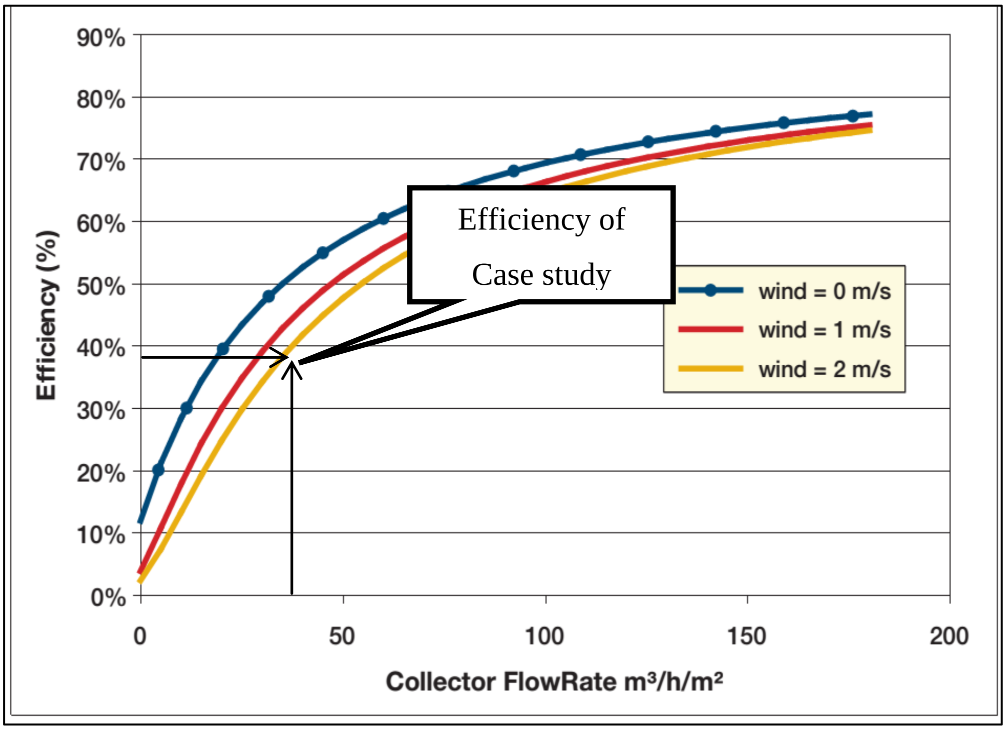

Figure 3.18: Efficiency of Comparison between the case study results and Retscreen documentation adapted from Retscreen [7].

3.4.2.3 Solar utilization

The energy which reduces heating load is called Usable energy. Non- usable energy is removed by using by-pass damper that pulls air directly out.

Utilization factor, $f_{utilized,i}$ is introduced to determine the amount of solar energy that supply heating system. ΔT_{act} , the average actual temperature of solar collector is supplied through the system. ΔT_{avl} is the available temperature rise [7].

$$f_{utility,i} = \frac{\Delta T_{act}}{\Delta T_{avl}} \tag{3.26}$$

When Solarwall automation system is integrated with actual building management system, limit of maximum deliver temperature is $T_{del,max}$.

Available temperature rise is found using the formula given below.

$$\Delta T_{avl} = \frac{\eta G_{tilt,i}}{\dot{Q}_{coll}\ \rho C_p\ h_{sunlight,jan}} \tag{3.27}$$

ρ, C_p are given previously.

$T_{del,act}$ is defined by user and limited so as not to exceed $T_{del,max}$.

$$T_{del,avl} = (T_{amb} + \Delta T_{offset}) + \Delta T_{avl} \tag{3.28}$$

where T_{amb} is daily average outside temperature of the month, ΔT_{offset} is assumed as 3 ^{o}C [7].

$$T_{del,act} = \min\,(T_{del,max}, T_{del,avl}) \tag{3.29}$$

Table 3.8: Temperature increase of West part plenum air.

West Part Month	T_{amb} ^0C	ΔT_{act} ^0C	ΔT_{offset} ^0C	T_{avl} ^0C	$T_{del,max}$ ^0C	T_{actdel} ^0C	$f_{util.}$
January	6	4.1	3	13.1	49	13.1	1.0
February	5.7	3.4	3	12.1	49	12.1	1.0
March	7.5	3,6	3	14.1	49	14.1	1.0
April	11.8	6.3	3	21.1	49	21.1	1.0
May	16.2	8.4	3	27.6	49	27.6	1.0
June	20.6	0.0	0.0	0.0	0.0	0.0	0.0
July	23.1	0.0	0.0	0.0	0.0	0.0	0.0
August	23.3	0.0	0.0	0.0	0.0	0.0	0.0
September	20.5	10.9	3	34.4	49	34.4	1.0
October	16.5	6.3	3	25.8	49	25.8	1.0
November	11.5	4.0	3	18.5	49	18.5	1.0
December	7.6	2.5	3	13.1	49	13.1	1.0

Table 3.9: Temperature increase of East Part plenum air.

East Part	T_{amb}	ΔT_{act}	ΔT_{offset}	T_{avl}	$T_{del,max}$	T_{actdel}	$f_{util.}$
Month	^0C	^0C	^0C	^0C	^0C	^0C	
January	6	3.5	3	12.5	49	12.5	1.0
February	5.7	2.9	3	11.6	49	11.6	1.0
March	7.5	3.1	3	13.6	49	13.6	1.0
April	11.8	5.4	3	20.2	49	20.2	1.0
May	16.2	7.2	3	26.4	49	26.4	1.0
June	20.6	0.0	0.0	0.0	0.0	0.0	0.0
July	23.1	0.0	0.0	0.0	0.0	0.0	0.0
August	23.3	0.0	0.0	0.0	0.0	0.0	0.0
September	20.5	9.4	3	32.9	49	32.9	1.0
October	16.5	5.4	3	24.9	49	24.9	1.0
November	11.5	3.5	3	18.0	49	18.0	1.0
December	7.6	2.1	3	12.7	49	12.7	1.0

3.4.2.4 Active solar energy savings

In this task, determination of saving energy is done in day time for each month. Delivered solar energy each month is determined as given below, $Q_{solar,i}$.

$$Q_{solar,i} = \eta \ \ x \ G_{coll,january} \ x \ f_{util,january} \tag{3.30}$$

Annual active solar energy savings equal to sum active solar energy savings of all months [7]. According to the efficiency of solar collectors, active solar energy savings are given in Table 3.10 and Table 3.11.

$$Q_{solar} = \sum_{i=1}^{12} (\eta_i \, G_{coll,i} f_{util,i}) \tag{3.31}$$

Table 3.10: Active solar energy savings of West part.

West Part Month	Stored Energy kWh	Efficiency %	Fraction	Saving Energy Mwh
January	28695.15	41.03	1	11.77
February	23968.98	40.54	1	9.17
March	30805.785	41.88	1	12.90
April	55929.15	43.32	1	24.22
May	82338.48	44.07	1	36.29
June	119618.46	44.44	0	46.06*
July	100931.04	43.32	0	51.81*
August	91822.95	42.70	0	43.16*
September	91822.95	43.13	1	39.60
October	49825.215	41.54	1	20.69
November	27517.05	41.71	1	11.47
December	16790.22	41.03	1	6.88
			Total:	**173.59**

*Heating systems are not in use during these months according to Istanbul climatic condition

Table 3.11: Active solar energy savings of East part.

East Part Month	Stored Energy kWh	Efficiency %	Fraction	Saving Energy MWh
January	24569.05	38.22	1	9.39
February	20522.46	37.71	1	7.74
March	26376.195	39.10	1	10.31
April	47887.05	40.59	1	19.43
May	70498.96	41.38	1	29.17
June	88700.1	41.79	0	37.06*
July	102418.4	40.59	0	41.57*
August	86418.08	40.02	0	34.58*
September	78619.65	40.40	1	31.76
October	42660.805	38.74	1	16.53
November	23560.35	38.92	1	9.13
December	14375.94	38.22	1	5.49
			Total:	**139.02**

3.4.2.5 Recaptured energy from building's heat

With Solarwall installed on building, heat losses from the applied wall are recaptured. If the collector is not running, there is very small benefit with increasing RSI value of the wall. There are three situations of different energy savings.

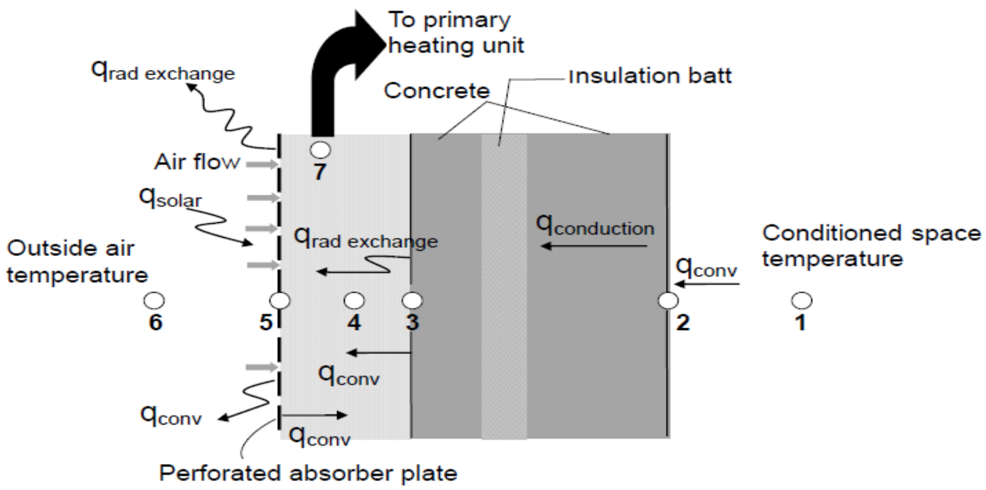

Figure 3.19: Recaptured energy transfer schematic[32].

While Solarwall is working in daytime, heat loss from building is recaptured and delivered through the conditioned space.

$$Q_{recap,op,daytime,i} = \frac{d_{op}}{7} x n_{day,i} x h_{op,daytime,i} \left(\frac{A_{coll}}{R_{wall} + R_{conv,i}} (T_1 - T_3)\right) \quad \textbf{(3.32)}$$

d_{op} and $h_{op,daytime,i}$ are described above and $n_{days,i}$ represents the amount days of month. A_{coll} is Solarwall surface area. The conduction through the building wall and the resistance to heat flow due to convection within the conditioned space are represented with R_{wall}, $R_{conv,i}$ [7].

T_4 is average air temperature in plenum;

$$T_4 = \frac{T_6 + T_7}{2} \quad \textbf{(3.33)}$$

T_1 is the average temperature of the inside and T_3 is measured on the exterior wall surface.

$$T_3 = \frac{(R_{conv,c})T_1 + (R_{conv,c} + R_{wall})T_4}{R_{conv,i} + R_{wall} + R_{conv,c}} \quad \textbf{(3.34)}$$

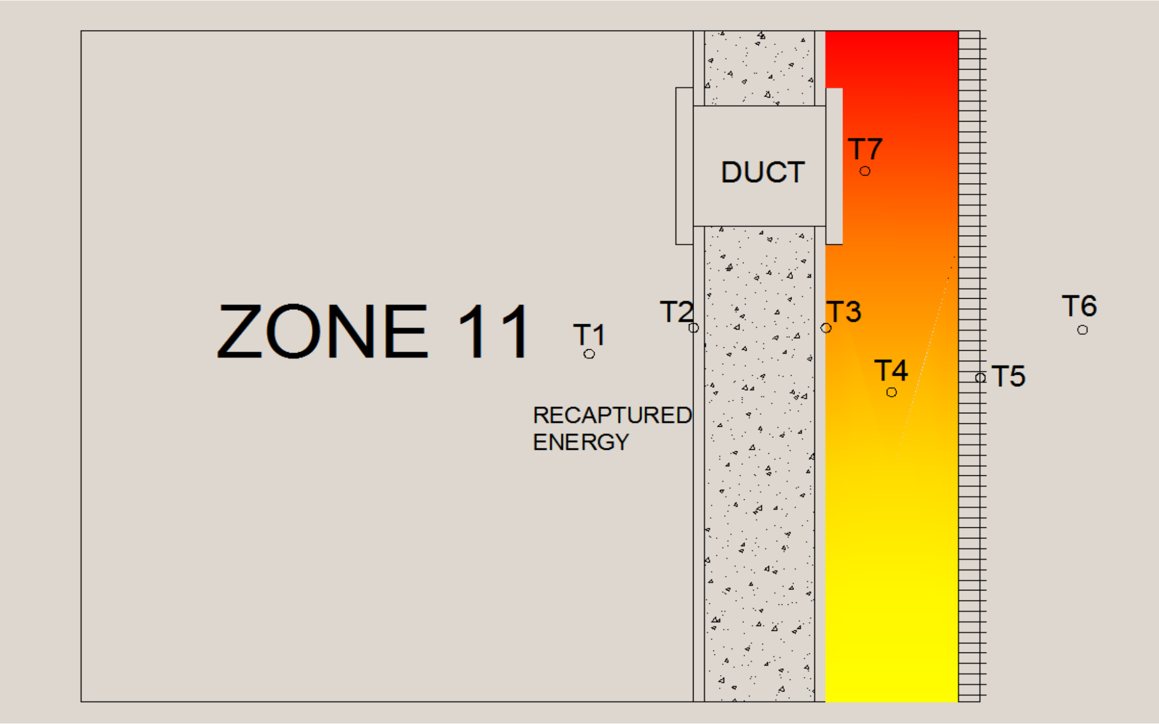

Figure 3.20: Section of Zone 11 when solarwall system works.

Average outside temperature of the month is represented by T_6

T_7 is described as $T_{del,act}$ as given equation 3.29 in solar utilization section.

The air film resistance for the ambient air is represented by $R_{conv,c}$

$$Q_{recap,op,nighttime,i} = \frac{d_{op}}{7} x n_{day,i} x h_{op,nighttime,i} \left(\frac{A_{coll}}{R_{wall}} \left(T_1 - T_6\right)\right) \quad \textbf{(3.1)}$$

If the Solarwall is not shut down in night time, heat losses are also recaptured. Occupied spaces need fresh air, therefore the Solarwall system is working during operation time.

In night time there is no heat gain from Solarwall; therefore plenum and outside temperature are assumed to be same. If operation stops and Solarwall fans do not work, there is a benefit in which the solar collectors increase the resistance of the wall due to reduced heat loss of building wall. Recaptured energy of each part is calculated as shown in Table 3.12 and Table 3.12.

Table 3.12: Recaptured energy of West part.

West Part Month	T_6 ^0C	T_7 ^0C	T_4 ^0C	T_1 ^0C	T_3 ^0C	$Q_{daytime}$ kwh	$Q_{nighttime}$ kwh
January	6	13.1	9.537	13.3	10.29	1233	4441
February	5.7	12.1	8.886	12.4	9.59	1147	3424
March	7.5	14.1	10.8	13.6	11.36	1141	3105
April	11.8	21.1	16.45	17.5	16.66	460	2503
May	16.2	27.6	21.88	24.6	22.43	1337	3385
June	20.6	34.2	27.4	27.2	27.36	-99*	2438*
July	23.1	37.9	30.51	30.5	30.50	-2*	2932*
August	23.3	36.9	30.08	31.2	30.30	518*	3465*
September	20.5	34.4	27.47	27.8	27.54	135	3446
October	16.5	25.8	21.14	24.7	21.86	1327	4522
November	11.5	18.5	15.02	17	15.41	640	3199
December	7.6	13.1	10.33	15.7	11.41	1698	5041
					Total:	**12922**	**33070**

*Heating systems are not in use in during these months for Istanbul climatic condition

Table 3.13: Recaptured energy of east part.

East Part Month	T_6 ^0C	T_1 ^0C	T_7 ^0C	T_4 ^0C	T_3 ^0C	$Q_{daytime}$ kwh	$Q_{nighttime}$ Kwh
January	6	12.8	12.5	9.24	9.96	996	3536
February	5.7	13.8	11.6	8.64	9.67	1440	3539
March	7.5	14.7	13.6	10.54	11.37	1447	3133
April	11.8	18.3	20.2	16.01	16.47	855	2441
May	16.2	25.5	26.4	21.31	22.15	1762	3204
June	20.6	27.9	32.8	26.68	26.92	514*	2305*
July	23.1	30.4	36.3	29.69	29,83	303*	2472*
August	23.3	32	35.4	29.34	29.87	1053*	3262*
September	20.5	28.8	32.9	26.71	27.13	733	3350
October	16.5	22.3	24.9	20.69	21.02	512	2734
November	11.5	17.6	18	14.73	15.30	792	3033
December	7.6	14.8	12.7	10.16	11.09	1256	3830
					Total:	**9797**	**28804**

*Heating systems are not in use in during these months for Istanbul climatic condition

3.4.3 Energy balanced solution of solarwall

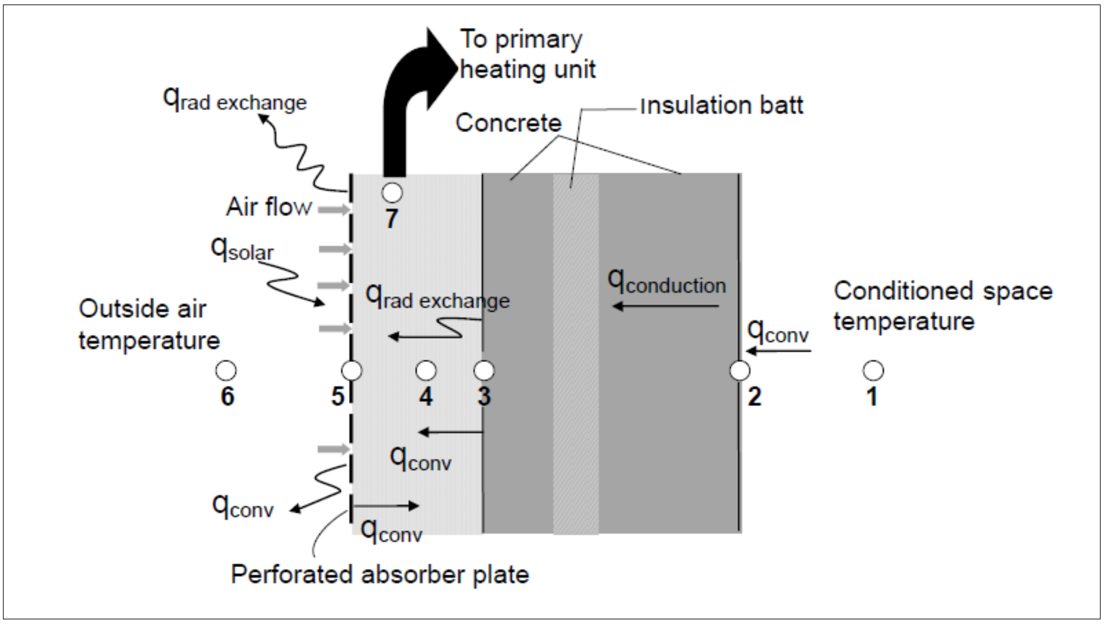

Figure 3.21: Section of solarwall system and temperature contributions [32].

To compare Retscreen solution with another simple solution which is energy balanced equations, it is assumed there are constant properties and one direction heat flow. According to the law of conversation of energy; inlet and output energies should be same. All components of energy are known to find delivering temperature through system.

$$\dot{E_{in}} = \dot{E_{out}} \quad \textbf{(3.36)}$$

$\dot{E_{in}}$ Includes these components;

$$\alpha IA \quad \textbf{(3.37)}$$

Where α is solar absorpitivity of solar collector, I is solar radiation on vertical surface and A represents the area of solarwall. This equation is the thermal radiation absorbed by the collector panels [32].

$$\frac{A_{coll}}{R_{wall} + R_{conv,i}}(T_1 - T_3) \quad \textbf{(3.38)}$$

The heat losses from Zone 11 and Zone 12 are recaptured. The resistance to heat flow due to convection within Zone 11 and Zone 12 is $R_{conv,i}$ (0.38 m^2 $^0C/W$), the resistance of wall due to conduction is R_{wall} [32]. R_{wall} (0.179 m^2 $^0C/W$) is found by using Table B.16

$\dot{E_{out}}$ Includes these components

$$(\frac{T_5 - T_6}{R_{conv,o}})A \quad \textbf{(3.39)}$$

From the solarwall to air, energy is transferred by convection. The resistance of air film by convection is $R_{conv,o}$ (0.14 m^2 $^0C/W$). A is the total area of collector [32].

$$\epsilon_5 \sigma A(T_5^4 - T_6^4) \quad \textbf{(3.40)}$$

Radiation transfers between collectors and air. ϵ_5 (0.90) is the emissivity of collectors. σ is Stefan-Boltzmann constant and A is the total area of the collector [32].

$$\left[\frac{A\sigma\,(T_3^4 - T_5^4)}{\frac{1}{\epsilon_3} + \frac{1}{\epsilon_5} - 1}\right] \quad \textbf{(3.41)}$$

Radiation transfers between wall surface and collector surface. ϵ_3 (0.90) is the emissivity of wall and is shown in Ecotect Analysis[32].

$$Q_{delivered} = m\rho c(T_7 - T_6) \quad \textbf{(3.42)}$$

Energy which is delivered into system is given above; m is flow rate of air, ρ is density of air and c is specific heat of air.

All equations [32] are used in energy balance as given below;

$$\alpha IA + \frac{A_{coll}}{R_{wall} + R_{conv,i}}(T_1 - T_3) = \left[\left(\frac{T_5 - T_6}{R_{conv,o}}\right)A + \epsilon_5 \sigma A(T_5^4 - T_6^4) + \frac{A\sigma\,(T_3^4 - T_5^4)}{\frac{1}{\epsilon_3} + \frac{1}{\epsilon_5} - 1} + m\rho c(T_7 - T_6)\right] \quad \textbf{(3.43)}$$

The heat losses of building wall are found as given below;

$$Q_{wall} = \frac{(T_1 - T_3)}{R_{wall} + R_{conv,i}} \quad \textbf{(3.44)}$$

T_4 which is the average temperature of plenum, is given below,

$$T_4 = \frac{T_6 + T_7}{2} \quad \textbf{(3.45)}$$

T_3 (temperature of wall surface) is found by using equation is given below;

$$T_3 = \frac{(R_{conv,c})T_1 + (R_{conv,i} + R_{wall})T_4}{R_{conv,i} + R_{wall} + R_{conv,c}} \quad \textbf{(3.46)}$$

T_5 is temperature of collector's surface and is found as given below;

$$\alpha IA = \left[\left(\frac{T_5 - T_6}{R_{conv,o}}\right)A + \epsilon_5 \sigma A(T_5^4 - T_6^4) + \frac{A\sigma\,(T_3^4 - T_5^4)}{\frac{1}{\epsilon_3} + \frac{1}{\epsilon_5} - 1} + \left(\frac{T_5 + T_4}{R_{conv,c}}\right)A\right] \quad \textbf{(3.47)}$$

To calculate the energy savings from solarwall, first assumption is made on T_7 .The flow chart including the steps followed are given in Figure 3.22. The iteration continues till initial T_7 temperature is equal or less to new T_7 [32]. Solar energy savings are calculated by equation 3.42 and the results are given in Table 3.14.

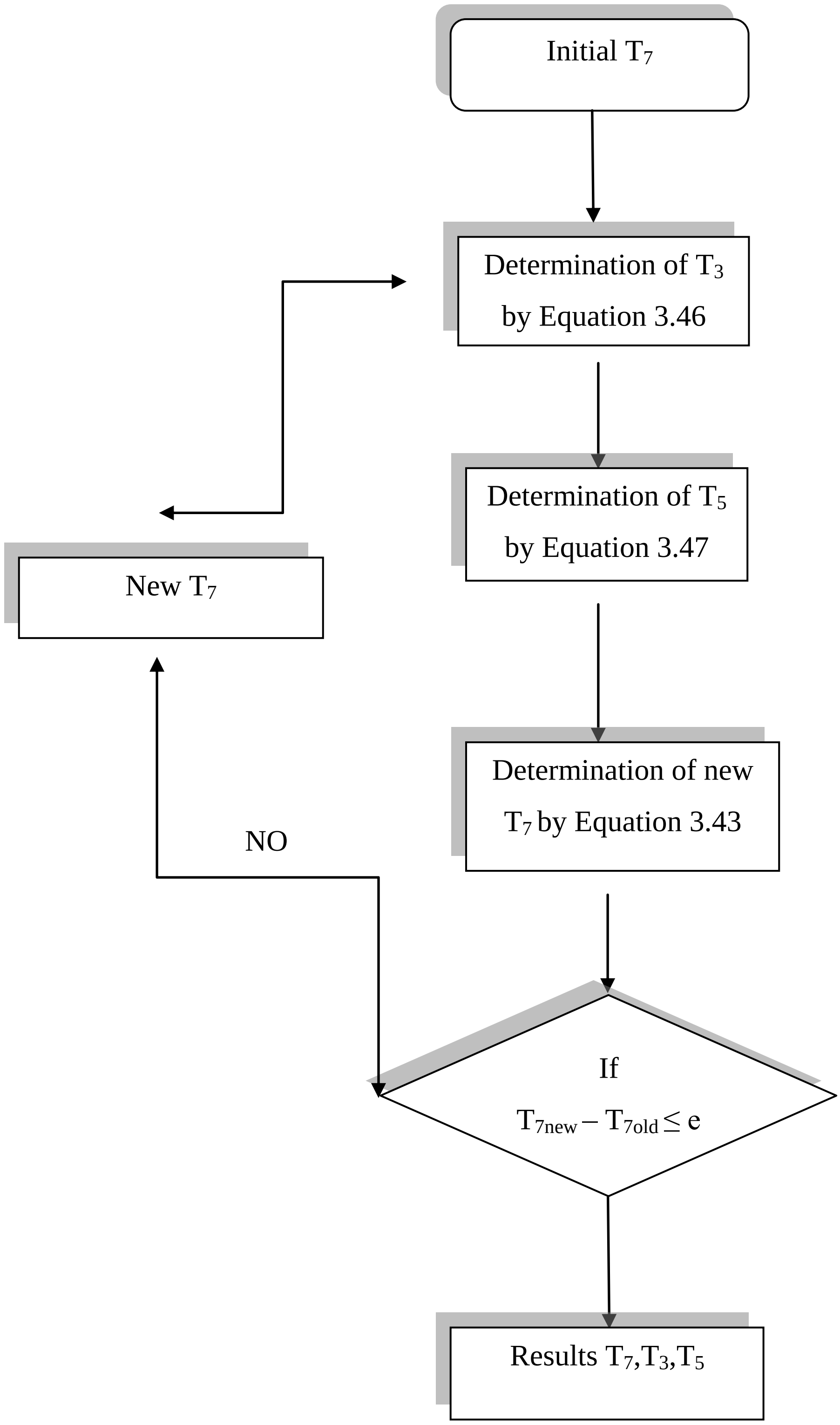

Figure 3.22: Flow chart of energy balanced equation.

Table 3.14 : Solar energy savings of West part and East part in daytime.

Month	West Part		East Part	
	T_7 ^0C	$Q_{daytime}$ kwh	T_7 ^0C	$Q_{daytime}$ Kwh
January	9.8	10986	9.5	9427
February	8.94	9337	9.11	9155
March	10.76	11708	10.64	10506
April	16.9	19647	16.63	17335
May	22.99	29468	22.61	25917
June	20.6	0	20.6	0
July	23.1	0	23.1	0
August	23.3	0	23.3	0
September	29.32	31934	28.82	28064
October	22.05	18272	21.47	15244
November	15.4	11104	14.87	8939
December	9.42	5082	10	6243
	Total:	**147541**		**130835**

3.4.4 Comparison of solutions

Results of Energy balance equations and Retscreen solutions are compared as given in Table 3.15. Comparison is based on the operation during the daytime. Therefore Retscreen results are considered to analyze the final energy saving because Retscreen software has very intense Solarwall technology application and its results. Efficiency of collectors is calculated by considering wind speed effect and properties of perforated material from Retscreen's specified solution

Table 3.15: Difference of Retscreen and energy balanced equations.

Month	Energy Balanced Equations kwh	Retscreen kwh	Difference %
January	20414	23396	-12.7
February	18492	20046	-7.7
March	22215	25805	-13.9
April	36982	44984	-17.7
May	55385	68566	-19.2
June	0.00	0.00	0.00
July	0.00	0.00	0.00
August	0.00	0.00	0.00
September	59998	72241	-16.9
October	33517	39067	-14.2
November	20043	22081	-9.2
December	11326	15340	-26.1
Total	**278376**	**323556**	**-16.0**

This comprasion includes only solar energy savings in daytime

3.5 Results

3.5.1 Overall efficiency of solarwall

When Solarwall is applied on the building, energy savings explained in the previous section as active solar energy saving and recaptured building heat are summed up as $Q_{total\ energy\ saving}$ and is given in

Table 3.16. This equation is valid on full time operation and does not need additional fans to integrated system.

$$Q_{total\ energy\ saving} = Q_{solar,i} + Q_{recap,op,daytime,i} + Q_{recap,op,nighttime,i} \quad \textbf{(3.48)}$$

Table 3.16: Total used solarwall energy in Zone 8.

	Produced Energy from Solarwall	Needed Energy for Zone 8	The Solarwall energy Utilization	Overall Efficiency of Solarwall
Month	kwh	kwh	kwh	%
January	31374	409568	31374	7.66
February	27011	424444	27011	6.63
March	32044	336228	32044	9.53
April	49929	123432	49929	40.45
May	75156	18669	18669	100.00
June	88279*	0	0	0
July	99086*	0	0	0
August	86140*	0	0	0
September	79038	625	625	100.00
October	46324	19584	19584	100.00
November	28314	152524	28314	18.56
December	24212	316677	24212	7.65
Total:	**393405**	**1801757**	**231767**	**12.86**

*On these months energy not in use but it can be used in cooling on further study

3.5.2 Investment cost

In existing building, the cost of installation of the Solarwall system is higher than installation cost of new building since displacing of expensive facade material increases the investment cost of Solarwall. Solar wall panel prices (including labor) are taken from Turkey’s solar wall distribution company in December 2013 as 140 €/m^2; this cost includes 90 €/m^2 for Solarwall materials and 50 €/m^2 for Labor. Applied area is 1420 m^2 and the overall cost of the system is shown in Figure 3.23.

Furthermore, Ducts are connected to AHUs. All duct materials shall be isolated by rock wool material to reduce heat losses in Ducts, supports, cabling etc... Price is assumed to be equal to 10 €/m^2 for December 2013. Fans are not required because existing system has fan to intake fresh air. Solely BSRIA and BMS systems modulate dampers.

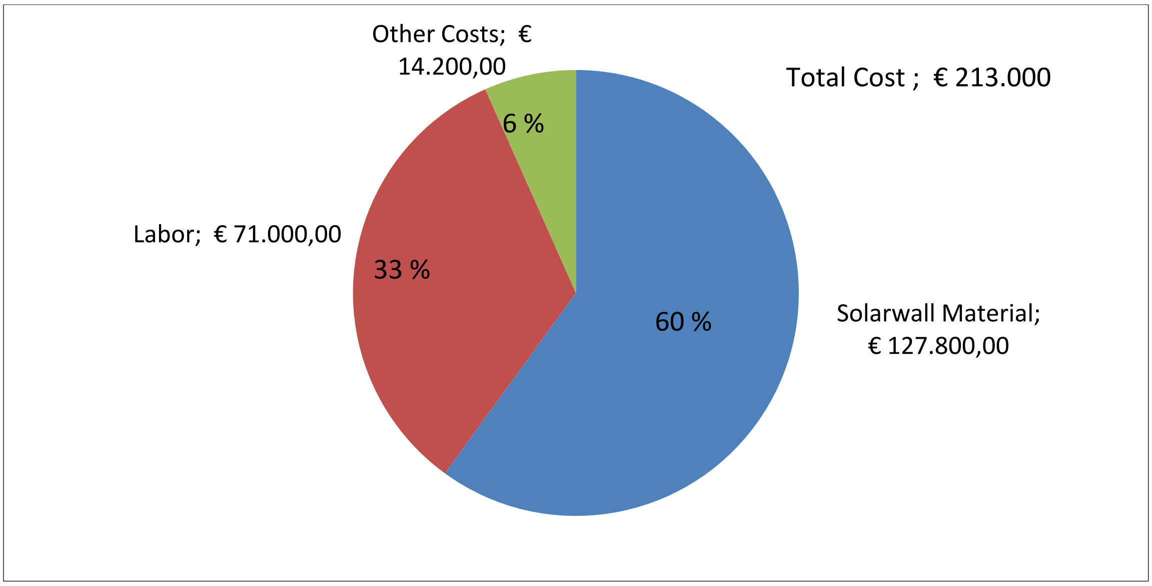

Figure 3.23: Investment cost of applied Solarwall.

3.5.3 Pay-Back time

The total investment cost of system is 213.000 € in December 2013. There is no need for maintenance except air unit distribution (fan bearings, belts and lubrication). Therefore the system requires minimum maintenance.

Solar wall lifetime is given 30 years as discussed in section 1.3. All payback calculations are performed accordingly.

Inflation rate: 2.5 %

Project lifetime: 30 years

General directorate of renewable energy supports projects which reduce energy by produced fossil fuels. The general directorate can cover 30% of project expenses.

Energy saving of every year is approximately 231.76 Mwh. If the heating energy is supplied by gas boilers instead of solar energy, its cost is estimated around 9.000-10.000 Euro each year. The defined annual saving is calculated with equation 3.49 and is given below.

$$Q = \eta \text{ x } \dot{m} \text{ x } h_{\text{natural gas}} \qquad \textbf{(3.49)}$$

where Q is delivered heating energy (kWh), η is efficiency of boiler which is assumed to be equal to 0.94. $\dot{m}$ is feeding natural gas volume (m^3) and $h_{natural\ gas}$ represents the lower heating value of natural gas and is equal to 9.045 kWh/m^3 .

$$231767\text{ kwh} = 0.94 \text{ x } \dot{m} \text{ x } 9.045 \text{ kWh/m}^3$$

m = 27259 m^3 (estimated annual consumption of natural gas)

Current price of natural gas = 0.333 € [34]

After installing Solarwall, payback time is 14 years; the graph is given in Figure 3.24.

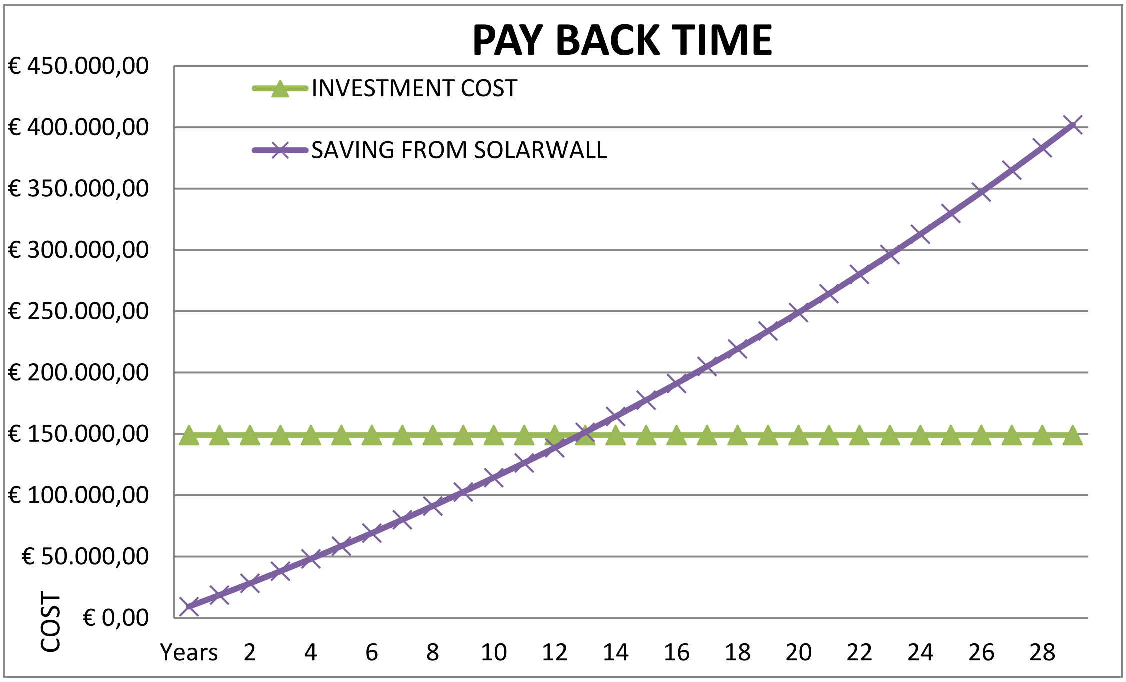

Figure 3.24: Payback time is developed by Excell.

3.5.4 Energy performance of the building

The energy consumption per square-meter indicates the energy performance of a building. In accordance with "Energy Efficiency Law No. 5627" and "Energy Performance of Buildings" Regulation, the energy consumption of the buildings shall be calculated and unnecessary wastage shall be avoided. When energy consumption is calculated, the consumption of energy related to heating-cooling, air-conditioning, hot water and lightening is calculated [35].

The energy performance of the building is determined according to the reference values found in Table 3.17 [35]. Since the airport is located in İstanbul, 2nd region and classified as a commercial building per activity, the reference value which shall be taken is 750 kWh/m^2 year [35].

Table 3.17: Reference indicator according to primary energy (RG: kWh/m year)[35].

Building Types	**Intended Purposes**	**1. Heating District (RG)**	**2. Heating District (RG)**	**3. Heating District (RG)**	**4. Heating District (RG)**
Residential	Single family house	165	240	285	420
	Apartments	180	255	300	435
Service Buildings	Office Buildings	240	300	360	495
	Education and training buildings (Schools, Dormitories, Sport center)	180	225	300	450
	Hospitals	600			
Commercial Buildings	Restaurants, Hotels Mall, Trade Centers	750			

Table 3.18: According to energy consumption, energy category [35].

Building Energy Category	**Ep Ranges**
A	0-39
B	40-79
C	80-99
D	100-119
E	120-139
F	140-174
G	175

EP: kWh/m^2 year

$$\mathrm{Ep,EP} = 100 \times (1 - (\mathrm{EP_r} - \mathrm{EP_a})/\mathrm{EP_r} \quad \textbf{(3.50)}$$

In above equation, Ep,EP is the energy performance of the building. EP_a and EP_r are the per-square-meter energy consumption of actual and reference buildings, respectively.

In order to find the energy class of the building, a relationship is established between the lightning, air-conditioning, heating-cooling annual energy per-square-meter energy consumption as shown in Table 3.18. After the energy class of the building is found, it is determined how much of an increase in the energy class by the Solarwall system provides.

As we have taken only the departure waiting saloons (Zone 8) of the building into account in our calculations, the per-square-meter annual heating and cooling energies of that section are taken from Table 3.2.

Annual heating energy consumption: 308.70 kWh/m^2 year

Annual cooling energy consumption: 104.98 kWh/m^2 year

The calculation of lightning energy consumption is done by using the formula according to EN 15193 standards [36].

$$W_{L,t} = (P_n \times F_c) \times \frac{[(t_D \times F_o \times F_D) + (t_N \times F_o)]}{1000} \mathrm{kWh} \quad \textbf{(3.51)}$$

$W_{L,t}$ = Annual lightning energy consumption per square meter.

P_n ; Lightning power per square meter for Zone 8 is referred to chapter 3.2.1 as 16 W/m^2 .

F_c ; Constant light control (Undimmed; Fc=1)

T_d = Daytime usage (According to Table 3.19 ; 4313 h)

T_n = Nighttime usage (According to Table 3.19 ; 4446 h)

F_o = Use factor (Manual opening = 0.95) [36]

F_D = Daylight dependency factor (No use in lightning while sun strikes in daytime; F_D = 0)

Table 3.19: Monthly day and night times for İstanbul [36].

Months	1	2	3	4	5	6	7	8	9	10	11	12
Day Time(h)	9.6	10.6	12	13.3	14.5	15	14.6	13. 6	12.5	11	9.8	9.3
Night Time(h)	14.3	13.3	12	10.7	9.5	9	9.3	10.3	11.5	13	14.1	14.6
Days	31	28	31	30	31	30	31	31	30	31	30	31

$$W_{L,t} = (16\ W/m^2 \text{ x } 1) \text{ x } \frac{[(4446 \text{ x } 0.95 \text{ x } 0) + (4313 \text{ x } 0.95)]}{1000}$$

$W_{L,t}$ = 65.55 kWh/m^2 year

Conversion to primary energy is performed via natural gas boilers and the conversion factor is 1. The cooling is performed via chillers. First, energy consumption of a cooling unit of the device is found, then this value is multiplied with the factor of 2.58, since the lightning energy source is electrical energy [35].

EP_a = [(308.70 x 1) + ((104.98/5.5) x 2.58) + (65.55 x 2.58)]

= 527 kWh/m^2 year

EP_r = 750 kWh/m^2 year (Table 3.18)

$$Ep, EP = 100 \text{ x } (1 - (EP_r - EP_a)/EP_r$$

$$Ep, EP = 100 \text{ x } (1 - \frac{750 - 527}{750})$$

$Ep, EP = 70.2$ kWh/m^2 year

The Zone 8 of the building is class B according to energy classification is shown in Table 3.18. It is determined how much the annual energy consumption per square-meter of the studied region drops and whether the energy class changes, when the Solarwall system is used.

After solarwall application, energy performance of building will be improved. The improved energy performance is given below. Solar energy is used to heat space instead of natural gas.

$EP_{a,s}$ =[(231767kwh year / 5836 m^2) x 1] = 39.71 kwh/ m^2 year

$$Ep, EP_{new} = 100 \text{ x } (1 - \frac{750 - 487}{750})$$

$$Ep, EP_{new} = 64.9$$

Energy consumption per square meters of Zone 8 reduces from 70.2 to 64.9 which show better performance than previous situation of Zone 8. The reduction of energy consumption is 7.5 % per square meter in a year.

3.5.5 Emission reduction

Required heating energy of the building is produced by combustion of fossil fuels. One of the aims of installing Solarwall system is to reduce greenhouse gas emissions with 231.76 Mwh energy saving. Many countries that signed Kyoto Protocol have some responsibilities to reduce emissions. Therefore governments support private companies which tend to renewable energy.

Solar wall shows us how much greenhouse gases release to atmosphere is reduced as below. In our country, most of power plants are operated with coals. According to Green Gas Protocol, emission factor (EF) of natural gas is 0.00188496 tons of CO_2/ m^3 fuel for stationary combustion. Annual amount reduction of emissions can be found as given below [37].

$$\text{Emission } (\text{tonnes}_{co2}) = \dot{m} \text{ x EF} \qquad \textbf{(3.52)}$$

$$\text{Emission } (\text{tonnes}_{co2}) = 27259 \ \ m^3 \text{ x } 0.00188496 \text{ tons of } CO_2 / \ m^3$$

Emission = 51.38 tons of CO_2/year

By using this system every year estimated 51.38 tons of CO_2 gas emission will be prevented to release into air.

4. CONCLUSION

Solarwall is a system with a great potential of application future use. The system is yet to become popular in Turkey, with applications on only two buildings. In this study BISW system was identified based on the whole system efficiency. The results show that unglazed transpired collector system performs when it is integrated on the South wall of the building with the 12 % efficiency. According to Energy Performance of Buildings classification, the per square meter energy consumption of the building classifies it as a B-class with a value of 70 kWh/m^2 year. After the application of Solarwall system, this value reduces to 64.9 kWh/m^2 year. The reduction in the emission into the atmosphere is also calculated when Solarwall system is applied. As a result, a total of 51.38 tons of carbon dioxide emission reduction is determined. The pay-back period of 14 years, as found in this study, is too high to render itself as a profitable investment. The main reason is the high price of the panel per square-meter. In this study, the application of the panel on the facade of the unconditioned area reduces the amount of recaptured energy. In addition, the most advantageous time periods of application for this system are the clear and cold weather conditions. The main advantages of the Solarwall when compared to other renewable energies are the high absorption ratio and its ability to transfer most of the energy to air. As a result of its design with holes, efficiency of collectors is changed by flow rate and wind speed. In this study, efficiency of collectors is found very low because of low flow rate per m^2. If heating air is totally supplied by outside air, efficiency of collectors rises up % 80.

A further study could be the investigation of the use of solar energy captured in summer months for cooling purposes. By installing combined system with solarwall, system efficiency is much more than normal system.

The countries which have signed the Kyoto Protocol support the use of renewable energies. Similarly, the support from the state shall reduce the pay-back time of this system in our country as well. It is clear that this system will gain an increasing amount of popularity with decreasing panel prices and integration with different systems.

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APPENDICES

APPENDIX A: The used parameters of design heating and cooling system

APPENDIX B: The properties and figures of building's wall, glaze, roof and floor

Table A.1: Heat gains from people [31].

Activity	Places	Sensible Heat (W)	Latent Heat (W)	Total Heat (W)
Sitting	Theatre	65	30	95
Sitting Clerical	Offices hotels apartments	70	45	115
Walking slow	Mall	75	55	130
Walking standing	Banks Pharmacy	75	70	145
Resting	Restaurants	80	80	160
Exercise	Factory	80	140	220
Dance	Disco bars	90	160	250
Walking fast	Factory	110	185	295
Sport	Sport Center	210	315	525

Table A.2: Heat gains of lightning's and electrical devices [30].

Structure Types	Lightings W/m^2		
	Low	Normal	High
Apartments, Hotel Rooms	2.2	6.5	9.7
Museum, Library		10.8	21.5
Banks (except private rooms)	9.4	16.1	24.7
Malls	12.8	20.4	32.3
Restaurants	16.1	18.3	21.5
Pharmacy	10.8	19.7	26.9
Gambling Saloons	12.3	26.9	58.1
Theatre	-	-	-

Table A.3: Heat gains of equipment [31].

	Equipment Heat Load		
Equipment	Max. Power W	By stand, W	Recommended Power, W
Computer	100-600	90-530	90-530
Card Reader	2200	1520	1520
Monitor	2200-6600	2200-6600	2200-6600

Table A.4: Air change rate per person [30].

Places	Air change per person (m^3/h)
Passenger saloons	30 m^3/h
Offices	50 m^3/h
Conferences and meeting saloon	36 m^3/h
Restaurants and Cafes	36 m^3/h
VIP	60 m^3/h
Hotel Rooms	100 m^3/h x room

Table A.5: Heat flux for different directions in İstanbul [30].

	Time		
Direction	08:00	12:00	16:00
WEST	50	50	500
EAST	500	50	50
SOUTH	50	200	50
NORTH	50	50	50
NORTH EAST	350	50	50
SOUTH EAST	350	150	50
SOUTH WEST	50	150	350
NORTH	50	50	350

Table A.6: Windows shade factors [30].

	No shade	Inside window shade, light	Interior window shade, dark	Exterior window shade
Glazed Windows	1.00	0.60	0.75	0.15-.0.20
Double Glazed Windows	0.90	0.50	0.65	0.15-0.20
Colored Windows	0.40-0.60			

Table A.7: Heat flux directions [30].

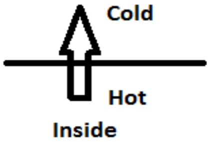
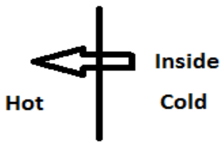
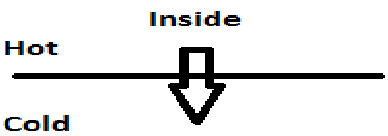
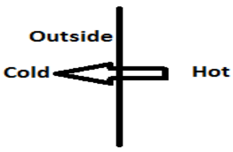
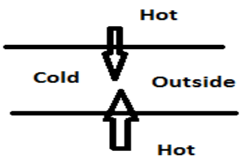
Surface and Heat Flow Direction			Heat Transfer Coefficient (kcal/m^{2}h C)
		Interior Surface, Heat flow up and horizontal	7
		Interior Surface, heat flow down	5
		All exterior surfaces	20

Table A.8: Δt $_{equivalent}$ values for roof in Istanbul [30].

Heavy Construction Roofs - Exposed Sun	A.M.				P.M.				
15 cm concrete	2.2	3.3	13.3	21.1	23.6	24.4	17.8	10	6.7
15 cm concrete + 5 cm isolation	3.3	3.3	11.1	18.9	23.3	24.4	18.9	11.1	7.8

Table A. 9: Δt $_{equivalent}$ values for walls in Istanbul[30].

Hours	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
C	D	B	D	B	D	B	D	B	D	B
South East	3.30	1.10	3.30	3.30	8. 90	5.60	10.00	6.70	10.00	6.70
South	1.10	0.60	1.10	1.10	2.20	0. 60	6.70	3.30	8.90	6.70
South West	3.30	1.10	2.20	2.20	3.30	1.10	4.40	2.20	7.80	5.60

Table A.10: Recommended air speed for comfort level [30].

Application	Noise Level	Main Duct		Secondary Duct	
	m/s	Supply (m/s)	Exhaust (m/s)	Supply (m/s)	Exhaust (m/s)
Residence	3	5	4	3	3
Hotel, Hospital	5	7.5	6.5	6	5
Private Offices, Library	6	10	7.5	8	6
Theatre, Concert Arena	4	6.5	5.5	5	4
Office, Restaurant, Malls, Banks	7.5	10	7.5	8	6
Stores, Cafeterias	9	10	7.5	8	6
Industry	12.5	15	9	11	7.5

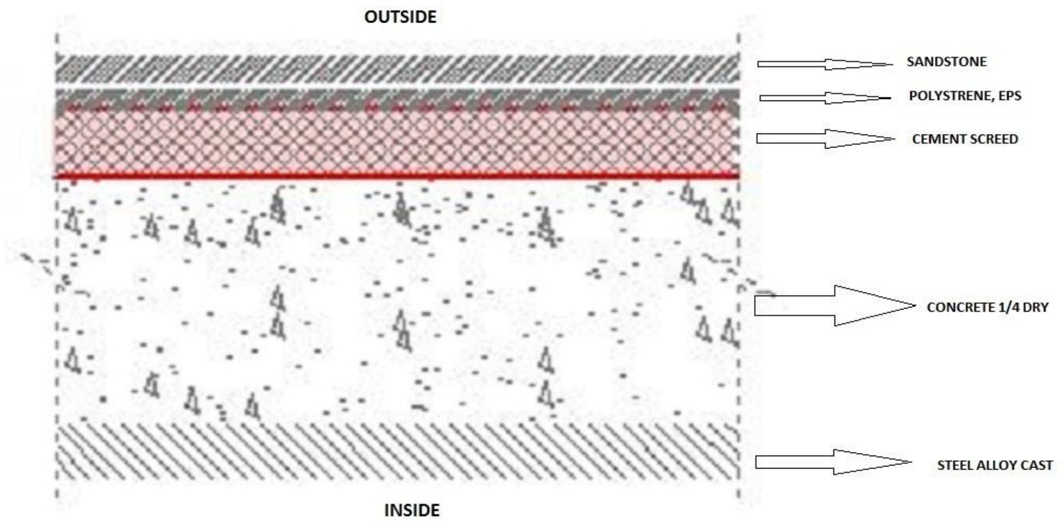


Figure B. 1: Roof section of Zone 8 [27].

Table B.11: Materials of roof [27].

Roof	Width (m)	Density kg/m3	Specific Heat J/kg.K	Thermal Conductivity W/m.K
Sandstone (Low Density)	0.015	2200	962.3	1.841
Polystyrene, Extruded (EPS)	0.05	35	1470	0.027
Cement Screed	0.05	2100	650	1.4
Concrete 1-4 Dry	0.125	2300	656.9	0.753
Steel Alloy Cast	0.004	7830	460.2	46.024

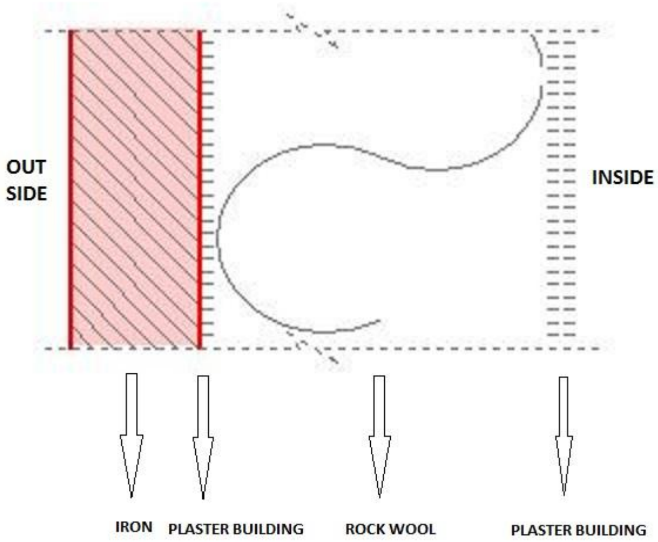


Figure B.2: Front wall section of Zone 8 [27].

Table B.12: Materials of front wall [27].

Front Wall	Width (m)	Density kg/m3	Specific Heat J/kg.K	Thermal Conductivity W/m.K
Iron (0 To 3000 C)	0.08	7870	447.7	71.965
Plaster Building (Molded Dry)	0.01	1250	1088	0.431
Rock Wool	0.2	200	710	0.034
Plaster Building (Molded Dry)	0.01	1250	1088	0.431

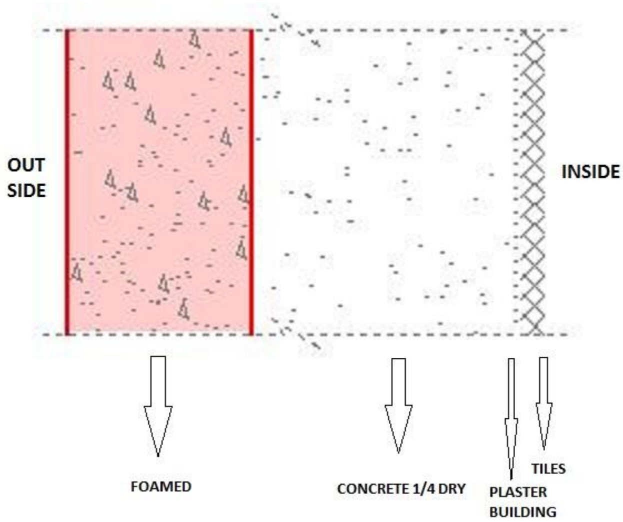


Figure B.3: Back wall section of Zone 8[27].

Table B.13: Materials of back wall [27].

Back Wall	Width m	Density kg/m3	Specific Heat J/kg.K	Thermal Conductivity W/m.K
Foamed	0.18	700	920	0.15
Concrete 1-4 Dry	0.25	2300	656.9	0.753
Plaster Building (Molded Dry)	0.01	1250	1088	0.431
Tiles	0.025	1200	1470	0.19

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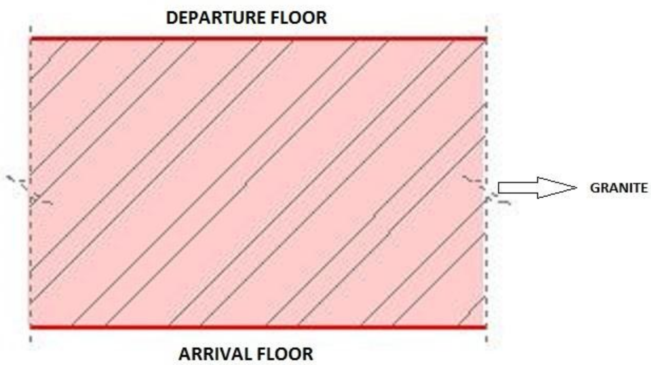

Figure B.4: Floor section of Zone 8 [27].

Table B.14: Materials of floor [27].

Floor	Width m	Density kg/m3	Specific Heat J/kg.K	Thermal Conductivity W/m.K
Granite	0.07	2880	840	3.49

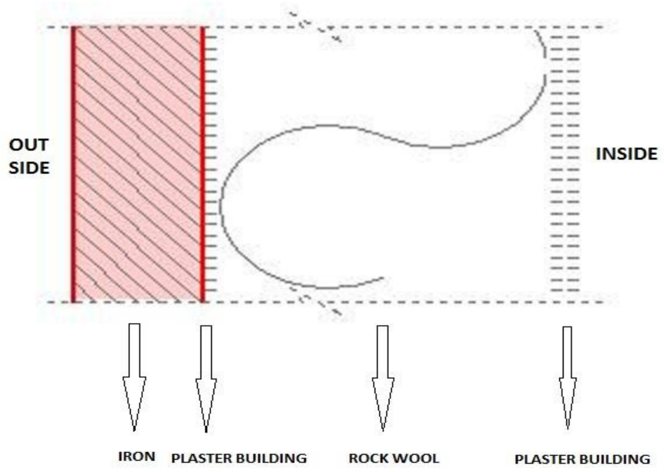

Figure B. 5: Windows section of Zone 8 [27].

Table B.15: Materials of windows [27].

Window	Width (m)	Density kg/m3	Specific Heat J/kg.K	Thermal Conductivity W/m.K
Glass, Granular Celluar	0.008	180	840	0.070
Air Gap	0.016	1.3	1004	5.56
Glass, Granular Celluar	0.016	180	840	0.070

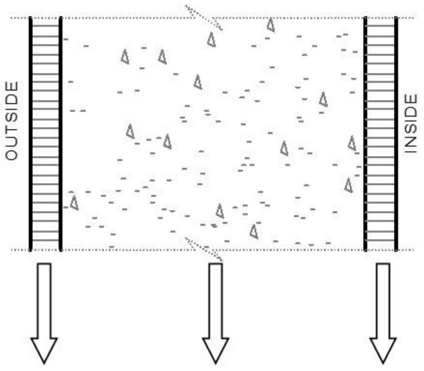

Figure B.6: Applied wall section of Zone 11-12 [27].

Table B.16: Materials of applied wall [27].

Layer Name	Width m	Density kg/m3	Specific Heat J/kg.K	Thermal Conductivity W/m.K
Plaster Building (Molded Dry)	0.01	1250	1088	0.431
Concrete 1-4 Dry	0.1	2300	656.9	0.753
Plaster Building (Molded Dry)	0.01	1250	1088	0.431

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