Isı Bilimi ve Tekniği Dergisi, 38, 2, 151-165, 2018
J. of Thermal Science and Technology
©2018 TIBTD Printed in Turkey
ISSN 1300-3615

ASSESSING EFFECTIVENESS OF INTEGRATED BUILDING DESIGN PARAMETERS ON ENERGY PERFORMANCE AND EMISSIONS IN HEALTH CARE FACILITIES BY MEANS OF BUILDING ENERGY MODELLING

MirParham POOYANFAR* and Hüseyin TOPAL**
*Gazi Üniversitesi Mühendislik Fakültesi Makina Mühendisliği Bölümü
06570 Maltepe, Ankara, p.pooyanfar@gmail.com
**Gazi Üniversitesi Mühendislik Fakültesi Makina Mühendisliği Bölümü
06570 Maltepe, Ankara, htopal@gazi.edu.tr

(Geliş Tarihi: 26.11.2017, Kabul Tarihi: 26.10.2018)

Abstract: The main purpose of healthcare facilities is to treat patients, enhance and maintain public health and help patients to spend a healthier life after their treatment. Yet considerably higher energy consumption rates in the healthcare facilities with respect to other commercial building types results in increased service costs which contradicts the mentioned goals. Providing the public with adequate, proper and timely health services may not be possible without cutting down preventable operation costs. In this research possible solutions for reducing energy consumptions of hospital buildings are investigated with the aim of decreasing the energy and consequently service costs. In this regard a prototype hospital building is studied by developing its energy model compliant with local codes and regulations. Later, this model is used as baseline to evaluate the enhancement of integrated design parameters like building orientation and window to wall ratio along with improvements to building systems which have a significant impact on building energy performance such as HVAC, lighting and building envelope systems. Moreover, effectiveness of each parameter is compared for four different climate zones. It was observed that by applying appropriate architectural, electrical and mechanical enhancements and utilizing renewable energy systems significant levels of energy conservation could be achieved and emission rates could be cut down nearly by half.

Keywords: Building energy efficiency, Health care, Hospital, Energy Modeling, Energy Conservation, Renewable energy.

BÜTÜNLEŞİK BİNA TASARIMI PARAMETRELERİNİN SAĞLIK KURUMLARININ ENERJİ TÜKETİM PERFORMANSI VE EMİSYON ORANINA ETKİSİNİN BİNA ENERJİ MODELLEME YARDIMIYLA DEĞERLENDİRİLMESİ

Özet: Sağlık kurumlarının temel amacı; bilindiği üzere kişi, aile ve toplumların sağlıklarının korunması, geliştirilmesi, hasta olanların tedavi edilmesi ve tedavi edilenlerin geri kalan yaşamlarını sağlıklı olarak sürdürebilmelerini sağlamaktır. İnsanların sağlık hizmetlerinden yeterince, yerinde, zamanında ve gereksiz masraflardan kaçınarak yararlanmaları önemlidir. Ancak sağlık kuruluşlarına ait binalarda enerji tüketimleri diğer ticari binalara göre çok daha fazladır ve bu nedenle de sağlık kurumlarının temel amacının aksine sağlık hizmetleri maliyeti yükselmektedir. Enerji maliyetinin azaltılmasını sağlamak maksadıyla yapılan bu çalışmada hastanelerdeki toplam enerji tüketimini azaltabilmek için, uygulanabilmesi muhtemel çözümlerin incelenmesi amaçlanmıştır. Bu bağlamda bütünleşik bina tasarımının önemli parametrelerinden olan bina yönü ve cam yüzey oranı ve ayrıca enerji tüketiminde önemli etkisi olan bina kabuğu, HVAC ve aydınlatma sistemleri gibi bina bileşenlerinin iyileştirme olanakları incelenmiştir. Bu doğrultuda iyileştirmelerin her birinin uygulanması durumunda, TS-825 standardı ve Bina Enerji Performansı (BEP) yönetmeliği ve diğer ilgili standart ve yönetmeliklerde belirtilen asgari şartlara uygun yapılan bir binaya göre hangi oranda enerji tasarrufu elde edilebileceği farklı iklim bölgeleri için karşılaştırılmıştır. Bunun için mevcut bir hastane binası prototip olarak kullanılmış ve binanın enerji modeli EDSL TAS programında belirtilen standart ve yönetmeliklere uyumlu şekilde oluşturulmuştur. Daha sonra bu model referans alınarak planlanan iyileştirmelerin her birinin binanın yıllık enerji tüketimi ve emisyon oranına olan etkisi belirlenmiştir. Yapılan çalışma sonucunda hastane binalarında mimari, mekanik ve aydınlatma sistemleri için uygun tasarım ve uygulamaların gerçekleştirilmesi ve yenilenebilir enerji kaynaklarının kullanılması durumunda önemli oranlarda tasarruf elde edilmesinin mümkün olduğu ve emisyonların yaklaşık yarı yarıya azaltılabileceği görülmüştür.

Anahtar Kelimeler: Bina enerji verimliliği, Hastane, Enerji Modelleme, Enerji tasarrufu, Yenilenebilir enerji

NOMENCLATURE

BMS	Building Management System
CDD	Cooling Degree Day []
CO_2e	Annual CO_2 emission [kg-CO_2/year]
DCV	Demand Controlled Ventilation
DOE	Department of Energy
E_c	Annual cooling consumption [kWh]
E_{ele}	Annual electricity consumption [kWh/year]
E_h	Annual heating consumption [kWh]
E_i	Annual consumption of the i^{th} end use [kWh]
E_l	Annual lighting consumption [kWh]
E_m	Annual consumption of mechanical equipment [kWh]
E_{NG}	Annual natural gas consumption [kWh/year]
E_p	Annual plug/process load consumption [kWh]
E_s	Annual consumption for steam generation [kWh]
EUI	Energy Usage Intensity
F_{ele}	Electricity emission factor [=0.517kg-CO2/kWh]
F_{NG}	Natural gas emission factor [=0.198kg-CO2/kWh]
HDD	Heating Degree Day []
LPD	Lighting power density
NREL	National Renewable Energy Laboratory
Q_a	Annual consumption of the building [kWh]
S_g	Total glazing surface area of a building [m^2]
S_f	Total area of building façade [m^2]
TMY	Typical meteorological year
US EIA	United States Energy Information Administration
WWR	Glazing ratio of building façade [$=S_g/S_f$]

INTRODUCTION

Energy related concepts are becoming more and more important and critical each day because of their environmental and economic aspects. An enormous amount of effort and budget is being spent worldwide in order to reduce the energy consumption and its undesirable effects. This includes almost all industries and sectors from heavy industries to daily products and services concerning people's daily lives. In this regard one of the most considerable energy consuming industries is the building industry. According to statistics buildings consume 40% of world's total energy end use (Laustsen 2008; Vakiloroaya et al. 2014; Balaras et al. 2007), which makes them a great candidate to investigate and apply energy conservation measures. Prior to application these measures must be studied in detail for each building type and climate condition to assess their effectiveness and feasibility. Buildings consume energy to several different ends such as lighting, electrical equipment, refrigeration, HVAC etc. Each of these end uses is a potential field for energy conservation. The type of energy used to meet these demands are either on-site fossil fuel consumption or grid supplied electricity which in turn is produced from fossil fuel at its source in most cases. Therefore, both of these energy types which constitute a major part of the energy used to meet building energy demands result in greenhouse gas emissions. Buildings have a considerable share in the Carbon dioxide (CO_2) emissions of the European Union (Bujak 2010). By reducing the building energy consumption economic benefits could be achieved as well as minimizing buildings' environmental effects.

Nearly 50% of the energy demand of buildings is used to provide indoor thermal comfort (Vakiloroaya et al. 2014; Enteria & Mizutani 2011). As a result of population growth and increasing indoor environment quality and comfort standards soaring building energy demands are inevitable. This is the reason why buildings must reach highest possible levels of energy efficiency if ambitious energy and environmental targets are to be met. Each building considering its usage, whether it is an office, school, retail or hospital building and depending on the climate conditions of its location may have a different energy usage profile. In the studies regarding building energy consumption behavior these two important parameters have to be taken into account. Numerous studies have been conducted in order to develop a pattern for energy demand and consumption of different building types on academic and institutional level (Bujak 2010), (Chung & Park 2015; Ndoye & Sarr 2008; Anon 2016). Also several researches have been conducted regarding possible strategies for reducing energy demand and consumption of the buildings, i.e. optimization of HVAC system design (Seo et al. 2014) and using new technologies and methods (Enteria & Mizutani 2011; Jazizadeh et al. 2014).

Buildings based on their usage may present different consumption behaviors and have varying energy usage intensity (EUI). EUI reflects the annual energy consumption in the building per unit area. Buildings with higher EUI hold a substantial potential for application of energy conservation measures.

Hotels and hospitals are among building types with highest EUI according to various studies (Kong et al. 2012; Chung & Park 2015). From these two building types hospitals are to be investigated in this study.

Hospitals are responsible for 6% of the energy consumed in services buildings in Europe and among different end-uses, HVAC systems has the greatest share (Teke & Timur 2014). HVAC systems of hospital buildings consume as much as 70% of total electric energy of the building (Hu et al. 2004). Electro motors, boilers, chillers, fans and pumps are a number of HVAC components that affect the energy use of buildings. For instance, while in most existing buildings boiler efficiencies are in the range of 65%-75%, efficient replacements can have efficiencies up to 95% that can create a great energy saving opportunity (Teke & Timur 2014). Aside from HVAC components, there are several other building elements such as overhead lighting and building envelope which, if designed and operated more efficiently, could lead to serious amounts of energy and cost savings.(Bonnema et al. 2010; Bonnema et al. 2016)

The aim of this study is to investigate the effect of different energy conservation measures on annual energy consumption and emission levels of hospital buildings located in different climate zones of Turkey. Several enhancement cases are studied and effects of each case is presented, along with the case where all of the enhancement are applied simultaneously.

METHODOLOGY AND MODEL DEVELOPMENT

Following is a brief description of the approach used to carry out this study and some technical details regarding development of the energy model of the building.

General Approach and Methodology

The 775-bed public hospital located in Isparta, Turkey is used as prototype to investigate energy conservation measures and determine their effectiveness for different climate zones of Turkey. General information regarding the actual hospital building is presented in Table 1. Since several other public hospital buildings with similar project designs are built or are planned to be built in near future in a number of other cities the results of this study could be applicable for evaluating related design decisions.

Table 1 General information of the prototype building.

Building Name	Isparta Public Hospital
Location	Isparta, Turkey
Capacity	775 beds
Coordinates	38.0211° N, 31.0794° E
Altitude	1050m
Floors Below Grade	3
Floors Above Grade	10

An energy model of the building is developed using EDSL TAS software, in accordance with architectural design drawings of the building taking into account local and international standards and regulations for building envelope characteristics and systems. This model is then used as baseline to study the effect of several enhancements for different climate conditions. These enhancements include integrated design parameters like building orientation and building envelope fenestration ratio in addition to envelope, HVAC and lighting system enhancements. For all cases the model is run for five different climate conditions each represented by hourly weather data of a major city located in that climate zone. Ankara, Istanbul, Antalya, Erzurum and Samsun are the cities selected to represent the climate conditions of different regions in Turkey. Table 2 demonstrates the heating degree day and cooling degree day values for the cities that represent the climate zones. It should be noted that despite Istanbul and Samsun are categorized under the same climate zone in local codes, they are treated separately because of their different humidity characteristics.

Table 2 Heating and cooling degree day of studied cities

City	HDD15	CDD22
Ankara	2410	262
Erzurum	4267	20
Antalya	592	798
Istanbul	1590	286
Samsun	1536	267

Hourly analysis is carried out to determine the loads, demands, consumptions and emission rates together with detailed consumption patterns based on building component and energy type. Calculated annual consumption and emission rates are then used to evaluate the saving potential of each enhancement and to compare their effectiveness. Annual energy consumption of the building was determined in terms of on-site energy use, by Equation (1):

$$Q_a = \sum_i E_i \qquad (1)$$

Where:

Q_a	Annual consumption of the building [kWh]
E_i	Annual consumption of the ith end use [kWh]

Annual consumption values are calculated for all anticipated end uses of the building including electrical plug and process loads, lighting, steam generation, mechanical equipments such as pumps and fans, cooling and heating. Therefore:

$$Q_a = E_p + E_l + E_s + E_m + E_c + E_h \qquad (2)$$

Where:

Q_a	Annual consumption of the building [kWh]
E_p	Annual plug and process load consumption [kWh]
E_l	Annual lighting consumption [kWh]
E_s	Annual consumption for steam generation [kWh]
E_m	Annual consumption of mechanical equip. [kWh]
E_c	Annual cooling consumption [kWh]
E_h	Annual heating consumption [kWh]

CO_2 emissions on the other hand are calculated taking into account the fuel type related to each end use. Two types of energy source were considered for the building; electricity and natural gas. Grid supplied electricity provides the lighting, plug and process loads, steam generation, mechanical equipment and cooling demands while natural gas provides the heating demand of the building which also includes service hot water demand.It should be noted that both fossil fuel or electrical boilers are alternatively used for steam generation in healthcare facilities. To avoid fluctuations in steam quality and considering ease of maintenance electrical systems are incorporated in the actual building design and similar public hospitals, thus reflected accordingly to the building models.

Different coefficients were used to determine emissions related to each energy source taking in to account their primary energy demand. As a result annual CO_2 emission for each case is calculated using Equation (3):

$$CO_2e = F_{ele} \times E_{ele} + F_{NG} \times E_{NG} \qquad (3)$$

Where:

CO_2e	Annual CO2 emission [kg-CO_2/year]

E_{ele} Annual electricity consumption [kWh/year]
E_{NG} Annual natural gas consumption [kWh/year]
F_{ele} Electricity emission factor [=0.517kg-CO_2/kWh], (Pout 2012)
F_{NG} Natural gas emission factor [=0.198kg-CO2/kWh], (Pout 2012)

Baseline Case Model

In order to develop an energy model for a building several inputs have to be taken into account consisting of building geometry, weather data, internal conditions, internal gains, building envelope characteristics, working schedules and details of HVAC system serving the building. In this study architectural design documents and drawings were used to develop a three dimensional model of the building including building exterior boundaries, zone distribution and fenestration size and orientations. General layout of the building geometry and sample zone distribution is shown in Figure 1 alongside with images of the actual building. This three dimensional model was then used in calculations for the baseline and all studied cases. Working schedules for lighting, occupancy, plug and process loads and HVAC systems were reflected identically between cases. Additionally, Minimum required outdoor and recirculation airflow rates were modeled consistent with ASHRAE Standard 170-2008 for space types where a required airflow rate is specified. For all other spaces outdoor airflow rates are determined in accordance with ASHRAE Standard 62.1-2007 (ASHRAE Standing Standard Project Committee 170 2008; ASHRAE Standing Standard Project Committee 62.1 2007). A summary of these airflow rates that are modeled identically for all studied cases is provided in Table 11. Considering the different climate conditions and cases included in the study HVAC equipment capacities were auto-sized based on demands with a sizing factor of one. Where sizing factors had to be revised to reduce the unmet load hours, the same factors were reflected to all case models in the same climate condition.

All other characteristics for the baseline case model including the envelope, lighting and HVAC systems were assumed to be compliant with minimum requirements of local standards and regulations. Where no local standard is present related requirements were taken from internationally accepted standards and reflected to the model. To this end baseline building envelope was modeled consistent with the requirements of local TS-825 standard for each climate zone (Turkish Standard 2009). A summary of these requirements is presented in Table 3**.**

Table 3 TS-825 Minimum Envelope Requirements for Different Climate Zones in Turkey (Units W/m2.K)

Climate Zone	U $_{wall}$	U $_{roof}$	U $_{floor}$	U $_{win}$
Zone 1 (Antalya)	0.70	0.45	0.70	2.4
Zone 2 (Istanbul/Samsun)	0.60	0.40	0.60	2.4
Zone 3 (Ankara)	0.50	0.30	0.45	2.4
Zone 4 (Erzurum)	0.40	0.25	0.40	2.4

On the other hand allowed lighting power densities and plug loads for each space type are modeled as required by National Calculation Methodology (NCM) modeling guide for Non Domestic Buildings (Communities & Local Government 2008) and HVAC system type and equipment efficiencies and numbers were reflected as required by ASHRAE Standard 90.1-2007 Performance Rating Method (ASHRAE Standing Standard Project Committee 90.1 2007). Table 11 shows a summary of space types included in the model and corresponding lighting power densities, outdoor and recirculation airflow rates and indoor comfort requirements for each space type. Moreover, some of the main features of the modeled HVAC system is presented in Table 10.

.

This constitutes the baseline building to which studied case are compared. After the energy model for the baseline building was generated, hourly simulations were run to determine the demand, consumption and emission levels. Later these results were compared to similar results for each improved case. To be able to form an understanding about the parameters affecting the energy consumption behavior of a building and to develop an opportunity to evaluate the effectiveness of each parameter several cases are studied. Each of the cases described below suggest an enhancement to the baseline building.

Model Validation

Prior to application of enhancements, the baseline case model was validated for one of the climate zones using independent consumption values from an existing hospital located in the same climate zone and data from existing literature. To this end, annual source EUI obtained from baseline case model for the city of Ankara is compared to similar values obtained from building management system (BMS) of LÖSANTE hospital also located in Ankara. Median reference values for hospital building EUI from Energy Star, a program managed by Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE), are also taken into account.(Anon 2016) Another reference value was obtained from Building Energy Performance Regulation in Turkey (BEP) which defines annual source EUI benchmark values for different building types.(Ministry of Public Works and Settlement 2007) Further, site EUI is compared for the baseline case model and data from National Renewable Energy Laboratory (NREL) commercial building benchmark models. A summary of gathered data is presented in Table 4. (Torcellini et al. 2008)

Table 4 Annual Energy Usage Intensity Comparisons

Source Annual Energy Usage Intensity (kWh/m2)	
Baseline model-Ankara	607
BEP Regulation in Turkey	600
Energy Star Median Reference	740
Lösante Hospital-Ankara	587
Site Annual Energy Use Intensities (kWh/m2)	
Baseline model-Ankara	333
NREL DOE Benchmark for Newly Constructed Hospitals	387

Additionally, breakdown of annual energy consumption by end-use is compared in **Table 5** for baseline model and published data from two studies conducted by United States Energy Information Administration (US EIA) and NREL operated by U.S. DOE on energy consumption in hospitals for the same climate zone. (Bonnema et al. 2010),(U.S. Energy Information Administration 2002)

Table 5 Annual Consumption Breakdown by End Use (%)

End Use	Baseline Model	US EIA Benchmark	NREL Benchmark
Electrical Equip.	10%	5%	14%
Lighting	9%	14%	6%
Non-HVAC Total	**19%**	**19%**	**20%**
Mechanical Equip.	33%	27%	33%
Cooling	9%	7%	13%
Heating	39%	47%	34%
HVAC Total	**81%**	**81%**	**80%**

Studying the outputs for the baseline model and consumption data of a hospital from the same climate region and existing literature it was confirmed that the developed energy model correctly represents energy consumption characteristics of a typical hospital and could be used for investing the effect of different enhancements to the building systems. Each of the studied enhancements are described in detail in the following sections.

Enhanced Case Models-Building Orientation

One of the characteristics of a building which is defined at the very first steps of the design is the building orientation. Site location, transportation and road access and zone distribution are some of the most important factors that define the orientation of a building during early design phase. Nevertheless, energy and comfort related issues do play a role in selecting the building orientation. To observe this role in a hospital building variations of building orientation with 90-degree rotations are generated and compared. Fenestration area and its ratio to total wall area on each façade of the baseline building is presented in Table 7.

Enhanced Case Model-Window to Wall Ratio

The ratio of window area to wall area in buildings is another parameter that can affect buildings' energy performance. Modern architectural designs tend to contain more glazing exteriors. Unless all required energy and comfort analysis are carried out in the design phase this may lead to undesirable performance results. To observe the effect of the envelope fenestration ratio on the building energy performance height of the windows are reduced by 20 and 40 percents considering the available standard window dimensions. This resulted in a 7% and 14% reductions in window-to-wall ratio respectively as shown in **Table 6**. Both cases are analyzed and compared to the baseline building. Window to wall ratio in a building is determined by dividing the total glazing surface area (S_g) by whole area of the building façade (S_f):

$$WWR = \frac{S_g}{S_f} \tag{4}$$

Table 6 Studied Cases for Different WWR

Case	WWR
Baseline	38%
20% Reduction in Window Height	31%
40% Reduction in Window Height	24%

It should be noted that since the actual building design and similar public hospitals do not incorporate daylight control for lighting system, which leads to the effect of building rotations and different WWR's has not be taken into account in the scope of this study. Including the effect of daylight control in building performance evaluation requires detailed daylight analysis which may be the subject of a separate study.

Table 7 Glazing Surface Distribution on Different Facades

Orientation	Window Area	Wall Area	WWR
Northwest	3703	11900	31%
Southeast	6605	15000	44%
Southwest	8090	21692	37%
Northeast	8518	21999	39%

Enhanced Case Model-Envelope

Aside from mentioned architectural aspects building envelope characteristics has the most significant effect on building performance in most building types. That is because it is the main medium for interaction of the building with its surroundings. This may not be the case for facilities with high ventilation and air change rate requirements such as hospital buildings but still will be an important issue that needs to analyzed in the design phase. In order to study its impact on the energy performance of health care facilities, insulation level of opaque envelope of the building is improved with respect to the minimum requirements of the local code (TS825) and more efficient glazing systems are reflected to the model. To this end, while all other characteristics of baseline building elements are conserved, insulation thicknesses are increased from 60 mm to 200 mm in 4th climate zone and to 150 mm in all other climate zones for vertical walls and from 120mm to 200 mm for the roof constructions in all climate zone except 4th climate zone where the suggested insulation thickness is 250mm. Also minimally compliant air-filled double glazing systems (Shading Coefficient=0.46) are replaced with argon filled double glazing with insulated frames (Shading Coefficient=0.31). (Data regarding glazing systems are obtained from Lawrence Berkeley National Laboratory (LBNL) Window 7.4 database). Table 8 compares the baseline envelope data with suggested envelope characteristics for the enhanced model. Obtained results will not only provide and understanding about effectiveness of envelope characteristics on energy performance of health care facility buildings, but also will help evaluate the competence of the local codes to exhort high performance building practices.

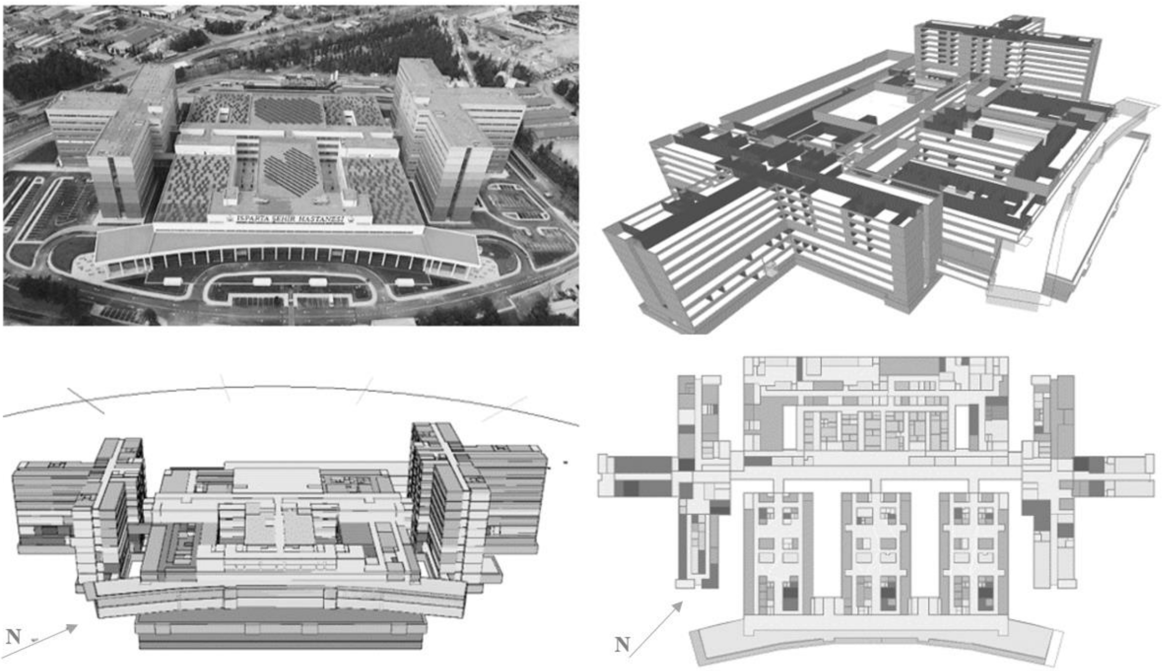

Figure 1 General Layout of the Building and Zone Distribution

Table 8 Envelope Characteristics of the Baseline and Proposed Buildings

Climate Zone	U $_{wall}$ (W/m²K)		U $_{roof}$ (W/m²K)		U $_{floor}$ (W/m²K)		U $_{win}$ (W/m²K)		Shading Coefficient	
	Local Code	Sugg. Value	Local Code	Sugg. Value	Local Code	Sugg. Value	Local Code	Sugg. Value	Local Code	Sugg. Value
Zone 1 (Antalya)	0.70	0.23	0.45	0.19	0.70	0.46	2.4	1.4	-	0.31
Zone 2 (Istanbul/Samsun)	0.60	0.23	0.40	0.19	0.60	0.46	2.4	1.4	-	0.31
Zone 3 (Ankara)	0.50	0.23	0.30	0.19	0.45	0.46	2.4	1.4	-	0.31
Zone 4 (Erzurum)	0.40	0.18	0.25	0.15	0.40	0.29	2.4	1.4	-	0.31

Enhanced Case Model-Lighting

After analyzing above mentioned parameters which mainly point out the importance of integrated design process, the effect of lighting system efficiency on the building performance is to be investigated. To this end by the assumption of choosing more efficient fixtures and by taking into account occupancy and programmable sensors for the applicable spaces a power adjustment factor of 10% is applied to the model as suggested in Performance Rating Method of ASHRAE Standard 90.1-2007 (ASHRAE Standing Standard Project Committee 90.1 2007). Lighting power densities (LPD) for some of the space types are presented in Table 9. Running hourly simulations for the updated model, obtained consumption results are compared to the baseline case. This modification to the energy model will help examine direct effect of choosing more efficient fixtures on lighting consumption along with its indirect effect on consumptions related to meeting the cooling loads. It should be noted that it is assumed that the applied enhancements do not affect the illuminance level of the spaces and fixtures only consume less energy while providing the same illuminance levels as the baseline case.

Table 9 Lighting power densities based on space usage (W/m^2)

Space Type	**Baseline Model**	**Enhanced Model**
Operation room	23.7	21.3
Patient room	7.5	6.8
Waiting room	14	12.6
Laundry	6.5	5.9
Physical therapy	9.7	8.7
Cafeteria/Restaurant	9.7	8.7
Nursery	6.5	5.9
Conference room	14	12.6
Nurse station	10.8	9.7
Laboratory	15.1	13.6
Examination room	16.2	14.6
Radiology	4.3	3.9
Emergency room	29.1	26.2
Triage	29.1	26.2
Intensive care	6.5	5.9
Sterile equipment	9.7	8.7
Medical equipment	15.1	13.6
Office	11.8	10.6
Corridors	10.8	9.7
Lobby	14	12.6
Locker room	6.5	5.9
Restroom	9.7	8.7
Plant room	16.2	14.6
Storages	9.7	8.7

Table 10 HVAC System Parameters for Baseline and Proposed Buildings

HVAC Parameter	Baseline Building	Proposed Building
System Type	CAV system with hot water reheat consistent with minimum equipment efficiencies from ASHRAE standard 90.1-2007.	VAV dedicated outdoor air system with terminal fan-coil units where room level recirculation permitted and VAV all-air system with reheat for the rest of spaces.
Air Handling Unit Specific Fan Power	1.2 W/l/s for supply and 1.0 W/l/s for return fans.	Same as Baseline. DCV and variable speed fans. Additional low pressure terminal unit fans.
Economizers	Applied to the model in all climates for possible systems.	Same as Baseline.
Heating Systems	Natural gas boilers with a nominal efficiency of 80% and hot water supply temperature reset based on outdoor temperature.	Natural gas condensing boilers with a nominal efficiency of 90% and hot water supply temperature reset based on outdoor temperature.
Chilled Water System	Water cooled centrifugal chiller with chilled water supply temperature reset with a COP of 6.1.	Water cooled centrifugal chiller with chilled water supply temperature reset with a COP of 7.
Pumps	Variable speed pumps with 75% efficiency and 180 kPa head for both cooling and heating systems.	Same as Baseline
Equipment Sizing	Auto-sized	Same as Baseline
Humidification	Electrical Humidifier	Same as Baseline
Dehumidification	By use of zone relative humidity (RH) sensors the cooling coils are automated to keep the RH value below 60% where required	Same as Baseline
Outdoor and Supply Airflows	In accordance with ASHRAE standard 170-2008 and 62.1-2007	Same as Baseline

Table 11 Space Type Categories and Modeled Lighting Power Densities, Airflow Rates (ASHRAE Standard 170-2008) and Indoor Comfort Requirements

Space Type / Parameter	Baseline Lighting Power Density (W/m2)	Plug and Process Load Density (W/m2)	Outdoor Air (l/s.person)	Outdoor Air (l/s.m2)	Outdoor Air (ACH)	Total Air (ACH)	All Air Exhaust Directly to Outside	Air Recirculation Room Unit	Minimum Relative Humidity	Maximum Relative Humidity	Indoor Heating Set Temperature (°C)	Indoor Cooling Set Temperature (°C)
Anesthesia gas storage	9.7	10.8	0	0.6	0	8	Yes	NR*	NR	NR	16	23
Cafeteria	9.7	1.1	3.8	0.9	0	0	NR	NR	NR	NR	20	25
Clean workroom/holding	11.8	21.5	2.5	0.3	0	4	NR	No	NR	NR	21	25
Conference room	14.0	1.1	2.5	0.3	0	0	NR	NR	NR	NR	21	25
Corridor/transition	10.8	1.1	0	0.3	0	2	NR	NR	NR	NR	21	23
Dining room	9.7	1.1	3.8	0.9	0	0	NR	NR	NR	NR	18	25
Examination/treatment room	16.2	10.8	2.5	0.3	0	6	NR	NR	NR	60	21	25
Food preparation center	12.9	199	0	0	0	10	NR	No	NR	NR	18	20
Laboratory	15.1	43.1	2.5	0.3	2	6	Yes	No	NR	NR	20	25
Laundry	6.5	5.4	3.8	0.3	0	10	Yes	No	NR	NR	18	-
Lobby area	14.0	1.1	2.5	0.3	0	0	NR	NR	NR	NR	18	25
Locker	6.5	2.7	2.5	0.3	0	10	NR	NR	NR	NR	21	25
Lounge	8.6	1.1	2.5	0.3	0	0	NR	NR	NR	NR	21	23
Mechanical/electrical/telecom.	16.2	1.1	0	0.6	0	0	NR	NR	NR	NR	-	-
Medical supply/medication room	15.1	10.8	0	0.6	0	4	NR	NR	NR	60	16	23
Nurse station	10.8	8.1	2.5	0.3	0	0	NR	NR	NR	NR	21	23
Nursery	6.5	10.8	n/a	n/a	2	6	NR	NR	30	60	23	25
Office	11.8	5.4	2.5	0.3	0	0	NR	NR	NR	NR	21	25
Operating suite	23.7	43.1	n/a	n/a	4	20	NR	NR	30	60	19.5	20.5
Patient room	7.5	10.8	n/a	n/a	2	6	NR	NR	NR	60	21	23
Pharmacy	12.9	10.8	2.5	0.9	0	4	NR	NR	NR	NR	20	25
Physical therapy	9.7	10.8	10	0.3	0	6	NR	NR	NR	65	17	25
Procedure room	29.1	43.1	n/a	n/a	3	15	NR	NR	30	60	19.5	20.5
Radiology/imaging	4.3	96.9	2.5	0.3	0	6	NR	NR	NR	60	20	25
Reception/waiting	14.0	1.1	2.5	0.3	0	0	NR	NR	NR	NR	21	25
Recovery room	8.6	21.5	n/a	n/a	2	6	NR	No	NR	60	23	25
Restroom	9.7	1.1	0	0	0	10	NR	NR	NR	NR	20	-
Soiled workroom or soiled holding	11.8	0.0	n/a	n/a	0	10	Yes	No	NR	NR	21	25
Sterilizer equipment room	9.7	64.6	0	0.6	0	10	Yes	No	NR	NR	16	23
Storage/receiving	9.7	10.8	0	0.6	0	0	NR	NR	NR	NR	-	-
Trauma/emergency room	29.1	43.1	n/a	n/a	3	15	NR	No	NR	65	23	25
Triage	29.1	10.8	n/a	n/a	2	12	Yes	NR	NR	60	21	25
Breakroom	11.8	1.1	2.5	0.3	0	0	NR	NR	NR	NR	21	23
Classroom	15.0	5.4	3.8	0.3	0	0	NR	NR	NR	NR	20	22
Critical or Intensive Care	7.5	10.8	n/a	n/a	2	6	NR	No	30	60	23	25

*Not Required

Enhanced Case Model-HVAC

Health care facilities are unique from the aspect that not only they have minimum outdoor air requirements, but minimum recirculation airflow rates are also required for different space types. Adding to this the obligation to discharge the exhaust air directly to outside in some space types together with humidity related requirements makes health care facilities a special case from HVAC systems point of view. Of course this brings with itself an opportunity to practice energy conservation measures. Here several improvements to baseline HVAC systems have been suggested. These improvements include decoupling the outdoor air from recirculation air and using room recirculation units where permitted by the ASHRAE Standard 170-2008, applying demand control ventilation (DCV) coupled with CO_2 sensors for all applicable zones, using high efficiency condensing boilers for heating and service hot water demands and using chillers with higher coefficients of performance. A summary of comparison between HVAC system specifications of baseline and enhanced case buildings is presented in Table 10.

Enhanced Case Model-Simultaneous Application of Enhancements

In addition to the cases mentioned above, two more cases are investigated in this research, one of which is the case where all enhancement are applied simultaneously to the baseline model. This includes reduction of WWR by 7% in addition to envelope, lighting and HVAC enhancements with the same technical details as describe in each relevant section. Building orientation has not been included in this case to be able to perform a meaningful comparison between different climate zones.

Enhanced Case Model-Photovoltaic Panels

The last studied case is where solar photovoltaic (PV) system with an area of 2250 m^2 equal to the system that is currently present on the building site is added to latter case. For this case energy generation potential is compared between different climate conditions for two separate renewable energy generation system types; constant angle PV and dual axis sun tracking PV systems. Typical meteorological year (TMY) data which has been used to conduct this study include hourly global and diffuse solar radiation and cloud cover values for each city. A solar conversion efficiency of 20% has been reflected for both PV system types with an inclination of 30 degrees and a solar reflectance value equal to 0.04. Figure 2 shows modeled inverter efficiency curve for PV systems. Further hourly simulations have been run to calculate annual generations. For the sun tracking case the panel will move its orientation to follow the sun's path during the day. Sun's path is calculated hourly using latitude and longitude values for each city. Figure 3 shows calculated sun position for a sample hour of the year (September 21^{st}, 09:00 am)

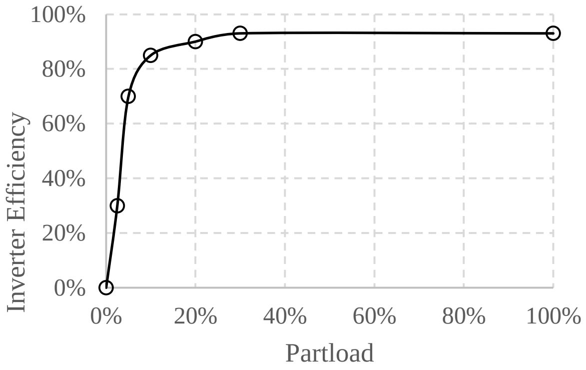

Figure 2 Inverter Efficiency Curve for PV System

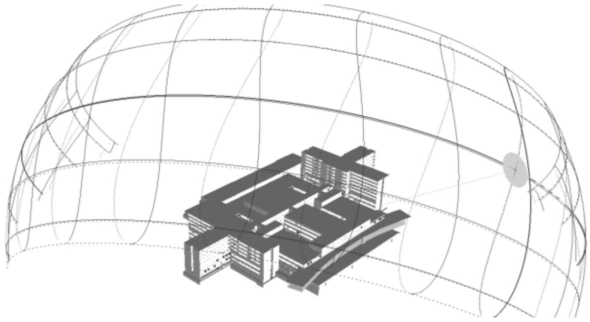

Figure 3 Calculated Sun Position for a Sample Hour of the Year (September 21st 9:00am)

RESULTS AND DISCUSSION

Running hourly simulations for each studied circumstance, hourly demands, consumptions and emission data are calculated and presented below. To achieve a more comprehensive and clear understanding from the energy consumption behavior of the building, results are compared and discussed separately for each enhancement case for different climate zones. Percentage change between best and worst scenarios is presented on result charts for each studied case.

Building Orientation

Four different building orientations are considered for the building in each climate zone and annual energy consumption and emission data are presented in Figure **4** and Figure 5 respectively, also stating percentage change between best and worst cases. As it can be seen for the case of Antalya where the weather is hot and humid the case in which facades with largest window area face Northwest and Southeast (90-degree rotation) produces the best performance by reducing the solar gain and the amount of direct sunlight entering the building, thus lowering the cooling demand. While for other cities all of which are heating dominated regions baseline case (0-degree rotation) yields the best performance since facades with largest window area face Southwest and Northeast allowing in higher amount of sunlight during heating season. This in turn reduces the heating demand and related consumptions and emissions.

Despite that the biggest difference between cases seem to be a minor one with only 2.5% energy saving potential between the best and worst cases (in case of Antalya) but considering the high energy consumption values of health care facilities and lifetime of buildings this minor difference ends up to be a significant one with an approximate emission reduction of 5400 tons and a cost saving equal to 1.3 million USD during a ten-year period. Therefore, should this process take place during the initial steps of the design process the obtained data may be useful for many purposes like site selection.

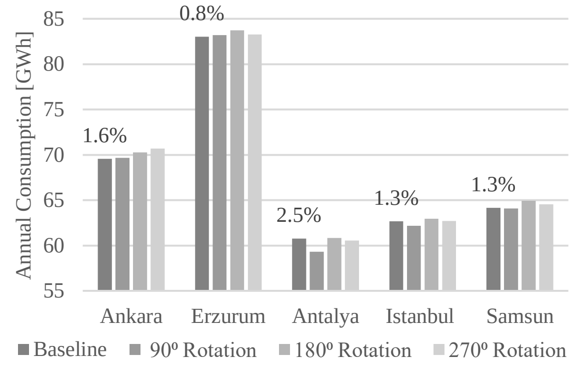

Figure 4 Annual Consumptions for Building Rotations in Different Cities

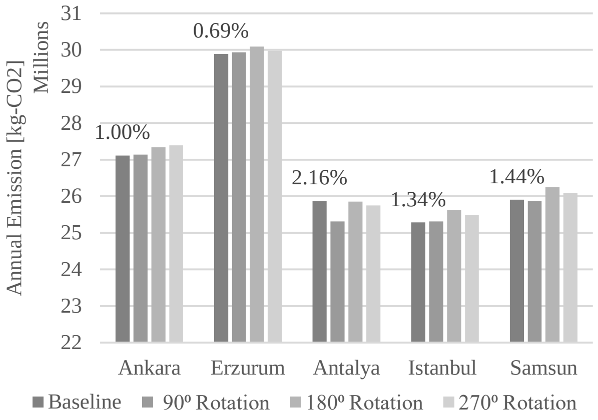

Figure 5 Annual Emission for Building Rotations

Window to Wall Ratio

Aside from the baseline case which is consistent with the actual building design two more cases are investigated for WWR of the building. Results regarding possible reductions in the fenestration ratio of the studied cases are presented in Figure 6 and Figure 7. It can be observed that for all climate zones reducing the transparent portion of the building exterior can reduce the global site consumption by more than 3%. While the same reduction trend is followed in all climates the effectiveness of such enhancement is found to be more significant for cities with severer climate conditions than mild ones.

Moreover CO_2 emissions could be reduced by as much as 930 tons per year by the window height modification. Again higher emission prevention rates could be obtained in extreme climate zones with Antalya being the city with the most emission cut in this case.

Detailed analysis of load breakdown of the building suggests that for cooling dominated climates this reduction is resulted from lower solar gains. While in heating dominated climates it is mostly related to better performance of the opaque envelope with respect to the transparent portion.

It should be noted that while these results reflect the general effect of window to wall ratio on consumption and emission rates, in order to optimise this ratio for each climate zone further detailed analysis is required taking into account the effect of daylight specially for the cases where daylight control is incorporated in the building design.

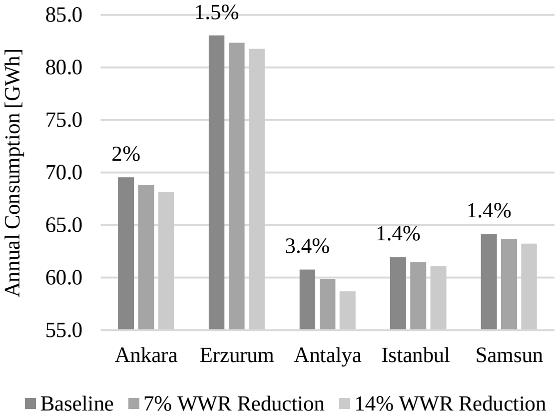

Figure 6 Annual Consumptions for Different Fenestration Ratios

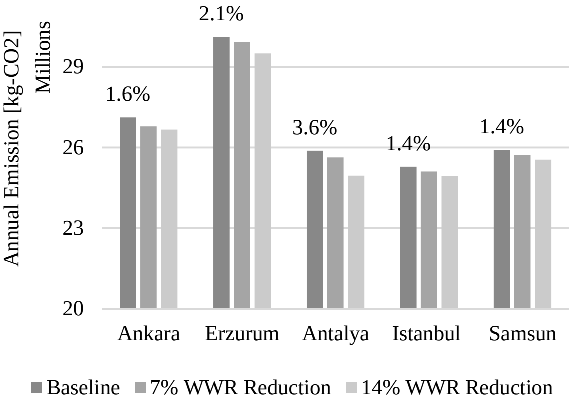

Figure 7 Annual Emissions for Different Fenestration Ratios

Envelope Enhancement

In the scope of this case enhancements are suggested for the building envelope including increasing insulation level of the opaque envelope and applying more efficient glazing system. Details of these improvements are discussed in Enhanced Case Model-Envelope section and Table 8.

Presented results in Figure 8 show that envelope enhancements lead to a minimum annual energy saving of 2.8% among all studied climate conditions which occurs for the city of Samsun. This number rises up to 5.7 % for Antalya and is above 3% for all other cities.

Emission rates were also found to be decreased to a considerable extent by the improved envelope . Starting from more than 800 tons for Samsun emission reduction numbers rise above 1500 tons in this case for Antalya as it can be observed from Figure 9**.**

Since building envelope defines how the building is affected from climate conditions, it will be meaningful to compare saving from envelope improvements with respect to ambient weather conditions. One of the main indicators designed to quantify heating and cooling energy demand with respect to ambient temperature is Heating/Cooling Degree Day (HDD/CDD) values. HDD and CDD values compare the mean ambient temperature to a standard temperature. Simply put, higher degree day value indicate more extreme outdoor temperatures. By comparing the emission reduction rates of the studied cities with respect to their HDD/CDD values one may conclude that while a minimum reduction of 3% could be achieved in all climate conditions, for the case of Antalya which holds the highest CDD value, reduction rate is more significant. That is where choosing a more efficient glazing system proves to be more crucial.

Building envelope is the main medium through which buildings interact with their environment. This leads to the expectation that envelope enhancements will have the most significant impact on the building energy performance. While this is valid for most building types, it may not be true in the case of hospital buildings. The main reason for this is exceedingly high energy use due to special ventilation and air change requirements in hospitals buildings.

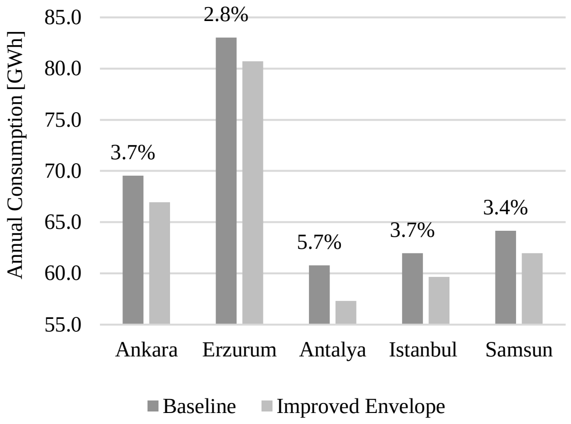

Figure 8 Annual Consumption for Enhanced Envelope Cases

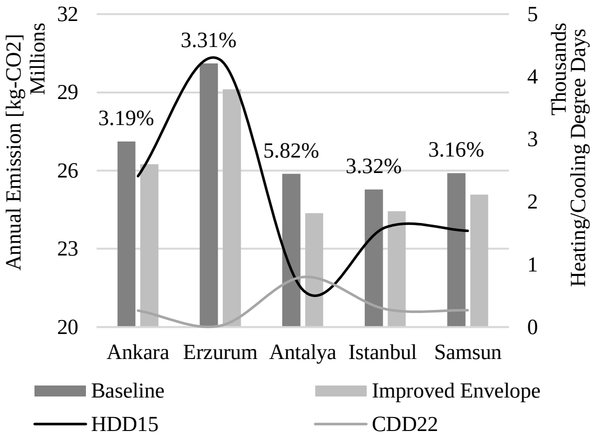

Figure 9 Annual Emissions for Envelope Enhancement Case

Lighting System Enhancement

By assuming more efficient fixtures in the design for all space types and utilization of occupancy and programmable sensors for applicable spaces and applying a power adjustment the calculations are repeated. Obtained results summarized in Figure 10 and Figure 11 show that choosing 10% more efficient lighting fixtures lead to an annual energy conservation of more than 1% all cities. This is equivalent to prevention of more than 300 tons of CO_2 emission. Studying the cooling loads points out that reduction of lighting power densities also reduces the cooling loads and consumptions related cooling system.

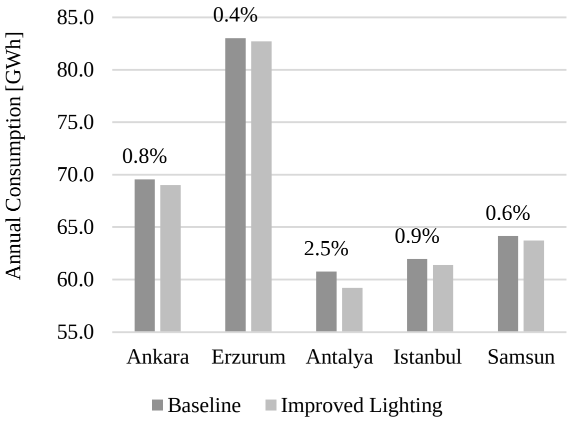

Figure 10 Annual Consumptions for Enhanced Lighting

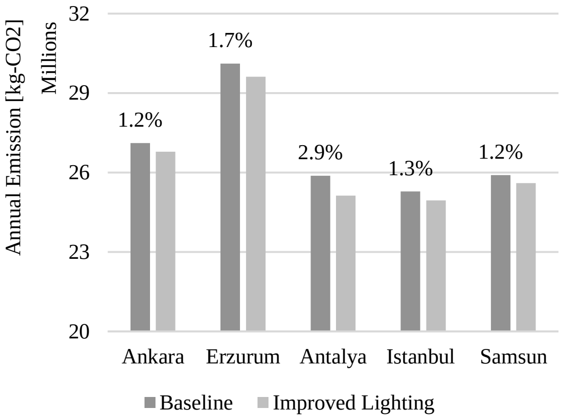

Figure 11 Annual Emissions for Enhanced Lighting Case

HVAC System Enhancement

Several improvements are reflected to HVAC system including air system structure, fan control and equipment efficiencies details of which are described in Table 10.

.

Indoor environment quality requirements of hospital buildings put them in a unique situation from energy consumptions aspect. Meaning that because of high outdoor and recirculation airflow rates HVAC systems have the biggest impact on the consumption levels. This can be observed from comparing obtained results between baseline and enhanced HVAC cases presented in Figure 12. The main difference between baseline and enhance HVAC cases is related to decoupling the outdoor fresh air from recirculation air. Such an impact is particularly significant because of high airflow requirements. Implementing more efficient boilers and chillers in the enhanced model as discussed in Table 10. results in lower heating and cooling consumptions for similar demands.

Obtained results show that HVAC enhancements improve the energy performance by more than 40% for all climate zones. CO_2 emissions are also reduced with similar effectiveness. Moreover comparing the emission rates to HDD/CDD as demonstrated in Figure 13 indicate that in heating dominated climates improvements prove to be slightly more effective.

Of course there are many more possibilities to reduce the HVAC systems' energy consumption such as reducing the supply and return duct pressure losses in order to reduce specific fan powers, using more efficient pumps and electrical motors, using innovative systems such as solar air heaters and many other options. The latter improvements are not applied to the enhanced case in this study to present the effect of improving main HVAC equipment more clearly.

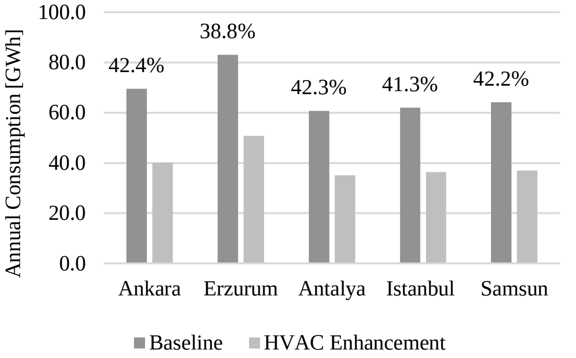

Figure 12 Annual Consumptions for Enhanced HVAC System

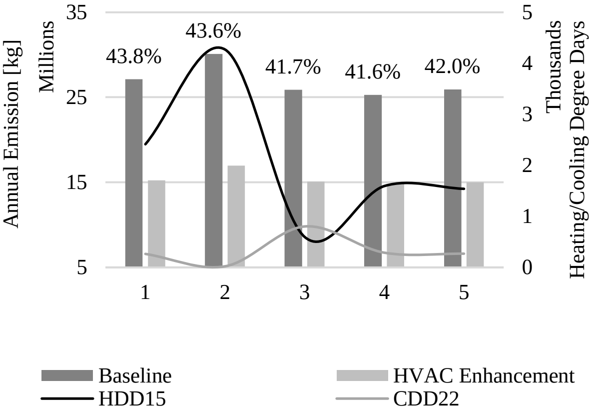

Figure 13 Annual Emissions for HVAC Enhancement Case

Simultaneous Application of All Enhancements

Following the analyses that has been demonstrated so far, in order to gain an understanding about effectiveness of an overall improvement to building envelope, lighting and HVAC systems simultaneous application of these cases, is studied. Details of these improvements in the scope of this case are identical to what was discussed for each individual case. In order not to deviate significantly from architectural aspects of the actual design the case of 7% reduction in window to wall ratio is taken into account. Additionally, to be able to carry out a meaningful comparison between results obtained for different climate conditions building orientations are not included in this case.

As demonstrated in Figure 14 and Figure 15 by simultaneous application of WWR reduction (by 7%) and envelope, lighting and HVAC enhancements as described in detail in the previous cases, an eye catching reduction of 45% could be achieved, while reducing the emissions by more than 11000 tons annually. Major part of this savings results from HVAC enhancements as discussed in the previous sections. More efficient HVAC systems along with reduced cooling and heating loads achieve by better envelope and lighting systems produce a significantly better energy performance for the building with respect to the baseline case.

It should be noted that when we look at the existing hospital buildings, in many cases, even some of the baseline measures are not present in the building resulting in a poor energy performance compared to the baseline case. Thus the effect of mentioned improvements will be even more significant in these cases.

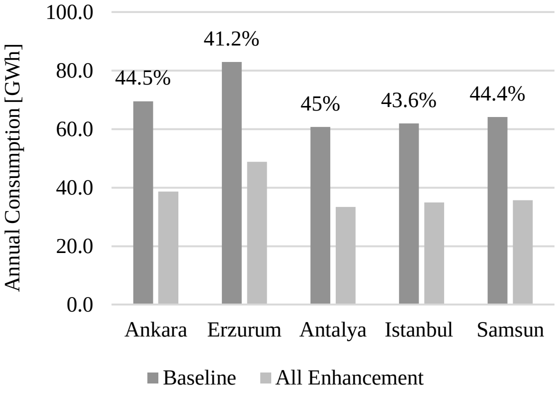

Figure 14 Annual Consumptions for All Enhanced System

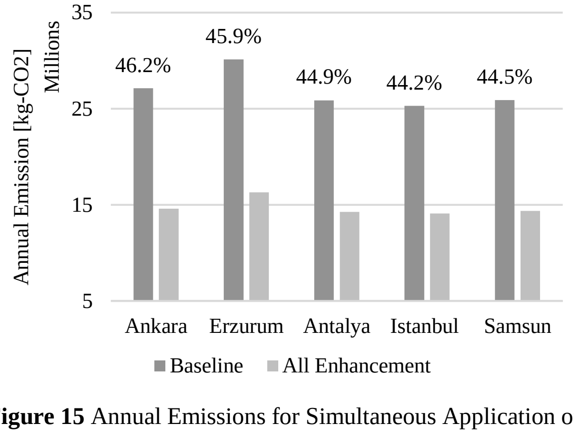

Figure 15 Annual Emissions for Simultaneous Application of All Enhancements

Photovoltaic System Addition

There are two major factors that make solar energy generation an ideal option for hospital buildings particularly for the climate regions that are subject to this study. First is the vast roof area of these buildings that provide considerable surface area which is one of the main hurdles for application of solar systems. Secondly, considering the annual solar irradiance of the region application of solar systems will have serious contribution to meeting the building energy demands. The annual electrical energy generation by two types of PV panels with surface area of 2250 square meters which is the actual capacity present in the building site and technical properties as specified in “Enhanced Case Model-Photovoltaic Panels” section, are compared for different cities and results are presented in Figure 166. Obtained results demonstrate a maximum possible annual generation above 750 MWh for constant angle PV systems while the same value rises to more than 900 MWh for sun tracking systems in the case of the city of Antalya which has maximum irradiation among studied cities. By looking at the emission levels in Figure 177 one may conclude that by using solar PV panels it is possible to prevent more than 400 tons of CO_2 emission annually. Despite their slightly better performance, tracking systems are not the prefered option in most cases because of higher initial investment costs and maintenance difficulties.

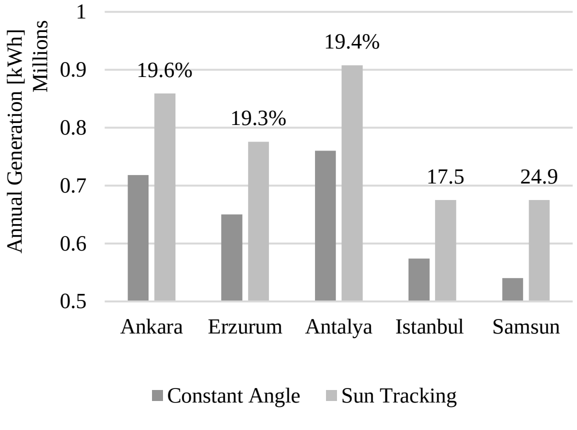

Figure 16 Annual Energy Generation by PV Systems

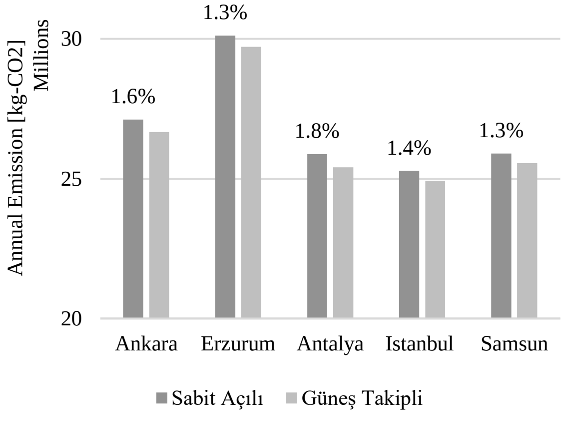

Figure 17 Annual Emissions for Application of Sun Tracking PV Systems

CONCLUSION

Health care facilities have a relatively high energy usage intensity among building types. Effect of several enhancements are studied on a prototype hospital building for all climate conditions of the region where the building is located. Results of the study show the importance of integrated design approach and its effects on the energy performance of the building by demonstrating the consequences of enhancing parameters such as building orientation and window-to-wall ratio. In other words, analyzing the energy model of the building in early design phase can lead to better and well informed decision making based on the building type and climate conditions. As we could see from the presented results for all building orientations, different orientations displayed the best performance depending on the climate region.

Envelope and lighting system enhancements also help to reduction of the annual energy consumption by a maximum of 5.7% and 3.4% respectively among different climates. Nevertheless because of the minimum outdoor and total airflow requirements HVAC system enhancements have the most significant contribution by creating energy saving levels above 40%. While simultaneous application of all suggested improvements can raise this level even further to 45%, implementation of renewable energy systems can meet up to 2.7% of the building’s energy demand.

Investigating the HVAC systems as the major energy consuming elements of the building shows that these systems have high equivalent full load hours of operation because of strict indoor environment requirements. This puts forward the idea that in order to achieve an even higher building performance in health care facilities combined heat and power (CHP) systems can play a significant role. Despite their high initial investment cost and maintenance difficulties, if selected with the right capacity and operated appropriately CHP systems can be a major upgrade to the building. For cooling dominated regions CHP system can be coupled with absorption cooling chillers to also meet the cooling demands. Performance and feasibility analysis of such systems is out of the scope of this study and is suggested to be taken into hand in further researches. All being said, it can be concluded that in order to achieve the best possible energy performance in health care facilities effect of all mentioned parameters should be investigated in the very first phases of a project to provide a solid foundation for making the best design decisions.

REFERENCES

ASHRAE Standing Standard Project Committee 170, 2008. ASHRAE Standard 170-2008 Ventilation of Health Care Facilities.

ASHRAE Standing Standard Project Committee 62.1, 2007. ASHRAE Standard Ventilation for Acceptable Indoor Air Quality. , 1(1041–2336).

ASHRAE Standing Standard Project Committee 90.1,

2007. ASHRAE 90.1 (Energy Standard for Buildings Except Low-Rise Residential Buildings). , 1.

Balaras, C.A. et al., 2007. Solar air conditioning in Europe-an overview. *Renewable and Sustainable Energy Reviews*, 11(2), pp.299–314.

Bonnema, E. et al., 2016. *Advanced Energy Design Guide for Large Hospitals*,

Bonnema, E. et al., 2010. Large Hospital 50 % Energy Savings : Technical Support Document Large Hospital 50 % Energy Savings : Technical Support Document. , (September).

Bujak, J., 2010. Heat consumption for preparing domestic hot water in hospitals. *Energy and Buildings*, 42(7), pp.1047–1055. Available at: http://dx.doi.org/10.1016/j.enbuild.2010.01.017.

Chung, M. & Park, H.C., 2015. Comparison of building energy demand for hotels, hospitals, and offices in Korea. *Energy*, 92, pp.383–393. Available at: http://dx.doi.org/10.1016/j.energy.2015.04.016.

Communities & Local Government, 2008. National Calculation Methodology (NCM) modelling guide (for buildings other than dwellings in England and Wales). *Communities and local government*, (November), pp.1–34.

Energy Star, 2016. Technical Reference U.S. Energy Use Intensity by Property Type. *Energy Star Portfolio Manager*, (September), pp.1–6.

Enteria, N. & Mizutani, K., 2011. The role of the thermally activated desiccant cooling technologies in the issue of energy and environment. *Renewable and Sustainable Energy Reviews*, 15(4), pp.2095–2122. Available at: http://dx.doi.org/10.1016/j.rser.2011.01.013.

Hu, S.C., Chen, J.D. & Chuah, Y.K., 2004. Energy Cost and Consumption in a Large Acute Hospital. *International Journal on Architectural Science*, 5(1), pp.11–19.

Jazizadeh, F. et al., 2014. User-led decentralized thermal comfort driven HVAC operations for improved efficiency in office buildings. *Energy and Buildings*, 70, pp.398–410. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.11.066.

Kong, X. et al., 2012. Research on the energy performance and indoor environment quality of typical public buildings in the tropical areas of China. *Energy and Buildings*, 48, pp.155–167. Available at: http://dx.doi.org/10.1016/j.enbuild.2012.01.021.

Laustsen, J., 2008. Energy Efficiency Requirements in Building Codes , Energy Efficiency Policies for New Buildings. *IEA Information Paper*, (March), pp.1–85. Available at: http://www.iea.org/g8/2008/Building_Codes.pdf.

Ministry of Public Works and Settlement, 2007. *Building Energy Performance Regulation in Turkey*,

Ndoye, B. & Sarr, M., 2008. Analysis of domestic hot water energy consumption in large buildings under standard conditions in Senegal. *Building and Environment*, 43(7), pp.1216–1224.

Pout, C., 2012. Proposed Carbon Emission Factors and Primary Energy Factors for SAP 2012. , (December 2011).

Seo, J. et al., 2014. Optimization of the HVAC system design to minimize primary energy demand. *Energy and Buildings*, 76, pp.102–108. Available at: http://dx.doi.org/10.1016/j.enbuild.2014.02.034.

Teke, A. & Timur, O., 2014. Assessing the energy efficiency improvement potentials of HVAC systems considering economic and environmental aspects at the hospitals. *Renewable and Sustainable Energy Reviews*, 33, pp.224–235.

Torcellini, P. et al., 2008. DOE Commercial Building Benchmark Models Preprint.

Turkish Standard, 2009. TS 825 - Thermal insulation requirements for buildings. , (ICS 91.120.10).

U.S. Energy Information Administration, 2002. Managing Energy Costs in Hospitals. *E Source*. Available at: https://www.eia.gov/.

Vakiloroaya, V. et al., 2014. A review of different strategies for HVAC energy saving. *Energy Conversion and Management*, 77, pp.738–754. Available at: http://dx.doi.org/10.1016/j.enconman.2013.10.023.

MirParham Pooyanfar has graduated as mechanical engineer from AmirKabir University of Technology (AUT) and is pursuing his master's degree on Efficient Energy System Design in Hospital Buildings. Parallel to his academic studies he has been working as building energy efficiency expert for the last five years. HVAC design, energy modelling, energy audit, commissioning and green building certification are his major activity fields. In the frame of these activities he has taken part in more than twenty building service design and R&D projects. His previous papers are:
Design and Economic Analysis of a Heating/Absorption Cooling System Operating with Municipal Solid Waste Digester: A Case Study of Gazi University, *Environmental and Climate Technologies*, 2013,
Techno-Environmental Assessment of Co-Gasification of Low-Grade Turkish Lignite With Biomass In A Trigeneration Power Plant, *Environmental and Climate Technologies*, 2014.

Address: Hacettepe Technopolis, 1st R&D building, No:18, Beytepe, Ankara, Turkey.
email: p.pooyanfar@gmail.com

Hüseyin Topal completed his first degree studies at Gazi University Engineering and Architecture Faculty at the department of Mechanical Engineering in 1989. He took part in the projects; "Investigation of the Causes of Air Pollution in Ankara and Measures for its Reduction" which are supported from NATO. In addition to these; he also completed his graduate studies within these projects. He made his PhD thesis according to the 'Circulating fluidized bed combustors'. Now he also works at Gazi Üniversity Engineering Faculty at the Department of Mechanical Engineering of Energy Fundamental as a staff member. He continues to work according to fluidized bed combustion systems, gasification, fuel combustion processing technologies, the environmental risk management, industrial air pollution control and solid waste management. Recently, he is working on biomass energy production, renewable energy sources and energy production from wastes and their environmental impacts. He also has theoretical and practical studies on plasma technologies. Plasma applications include plasma combustion, gasification and ozone production.

Address: Gazi University, Faculty of Engineering, Department of Mechanical
Engineering, 4th Floor, Room 423, Eti District, Yukselis Street, No:5, PO Box 06570,
Maltepe, Ankara, Turkey.
e-mail: htopal@gazi.edu.tr