ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

A NEW APPROACH TO INCREASE ENERGY EFFICIENCY OF LUXURY HIGH-RISE RESIDENTIAL BLOCKS IN COMPLEX BUILDINGS BY UTILIZING ADVANCED HVAC SYSTEMS

Ph.D. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

KARMA YAPILARDAKİ YÜKSEK KATLI LÜKS KONUT BİNALARININ ENERJİ VERİMLİLİĞİNİN GELİŞMİŞ MEKANİK SİSTEMLERDEN FAYDALANARAK ARTTIRILMASI İÇİN YENİ BİR YAKLAŞIM ÖNERİSİ

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Alpay AKGÜÇ, a Ph.D. student of İTU Graduate School of Science Engineering and Technology student ID 502102077, successfully defended the thesis/dissertation entitled “A NEW APPROACH TO INCREASE ENERGY EFFICIENCY OF LUXURY HIGH-RISE RESIDENTIAL BLOCKS IN COMPLEX BUILDINGS BY UTILIZING ADVANCED HVAC SYSTEMS”, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my sister Ecem, my faithful friend İlke and my dear cat Charlie,

FOREWORD

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December 2018 Alpay AKGÜÇ
(M.Sc Mechanical Engineer)

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ABBREVIATIONS

ACH : Air Change per Hour
AHU : Air Handling Unit
ASHRAE : American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAS : Building Automation System
BEM : Building Energy Modeling
BEPS : Building Energy Performance Simulation
BEP-tr : Building Energy Performance – Turkey
BIM : Building Information Modeling
BLAST : Building Loads Analysis and System Thermodynamics
BREEAM : Building Research Establishment Environmental Assessment Method
CFD : Computational Fluid Dynamics
CHP : Combined Heat and Power
COP : Coefficient of Performance
DC : Direct Current
DHW : Domestic Hot Water
DOE : Department of Energy
DXF : Drawing Exchange Format
EIC : Energy Identity Certificate
EN : Europian Standards
EPBD : Energy Performance of Buildings Directive
EPBD-recast : Directive 2010/31/EU of The European Parliament and of The Council of 19 May 2010 on The Energy Performance of Buildings
EU : European Union
GA : Genetic Algorithm
GNP : Gross National Product
gbXML : The Green Building XML Schema
GSHP : Ground Source Heat Pump
HRV : Heat Recovery Ventilator
HVAC : Heating, Ventilation and Air –Conditioning
ISO : International Organization of Standardization
ITU : Istanbul Technical University
LEED : Leadership in Energy and Environmental Design
LHV : Lower Heating Value
MPC : Model Predictive Control
MS : Member State
nZEB : Nearly Zero Energy Buildings
PE : Primary Energy
PV : Photovoltaic
SAVE : Specific Actions for Vigorous Energy Efficiency
SHGC : Solar Heat Gain Coefficient
SI : International System of Units
STC : Standard Test Conditions

TOE : Tonne of Oil Equivalent
TS 825 : Turkish Thermal Insulation Requirements
TUIK : Turkish Statistical Institute
TUBITAK : The Scientific and Technological Research Council of Turkey
UHI : Urban Heat Island
UK : United Kingdom
UNFCCC : United Nations Framework Convention on Climate Change
USA : United States of America

SYMBOLS

$C_{a,i}(j)$: Annual cost year i for component j
C_e : Energy cost
$C_e(i)$: Energy cost for year I
Cf_f : Conversion factor of any fuel
$C_G(\tau)$: Global cost referred to starting year τ0,
C_I : Initial investment cost
$C_{I(p)}$: Present value of initial investment cost
C_r : Running cost
C_m : Maintenance cost
C_o : Operational cost
CO_2 : Carbon dioxide
$f_{pv}(n)$: Present value factor of energy for calculation period n
H_2O : Water
I_{mpp} : Maximum power point current
I_{sc} : Short circuit current
$LiBr$: Lithium bromide
NH_3 : Ammonia
$n_\tau(j)$: Number of replacements of component or system j within the calculation period
PEC_e : Primary energy consumption for electricity
PEC_{max} : Maximum Power
PEC_n : Primary energy consumption for natural gas
PEC_{nRES} : Primary energy consumption from non-renewable sources
PEC_{RES} : Primary energy consumption from renewable sources
PEC_T : Total primary energy consumption
R_a : Area outdoor air rate
$R_d(i)$: Discount rate for year i
R_i : Inflation rate
R_p : People outdoor air rate
R_p : Rate of development of the price for products
R_r : Real interest rate
T_e : Conversion factor for electricity
T_f : Sum of total energy consumption of any fuel
T_n : Conversion factor for natural gas
T-vis : Visible transmittance
U-value : Overall heat transfer coefficient
$V_0(j)$: Investment costs for component or system j
$V_{f,\tau}(j)$: Final value of component j at the end of the calculation period
V_{mpp} : Maximum power point voltage
V_{oc} : Open circuit voltage
τ : Calculation period
$\tau_n(j)$: Lifespan or design duration for component or system j

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A NEW APPROACH TO INCREASE ENERGY EFFICIENCY OF LUXURY HIGH-RISE RESIDENTIAL BLOCKS IN COMPLEX BUILDINGS BY UTILIZING ADVANCED HVAC SYSTEMS

SUMMARY

Looking at the worldwide, the construction industry has undergone major developments and the building quantity has been rising gradually due to increasing human population so that more energy resources will be needed in the future. However, current energy resources are reducing day by day, and more energy resources mean more CO_2 emissions. Buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the European Union (EU). Therefore, the improvement of energy performance has become an important issue especially in the buildings recently.

In order to improve the energy efficiency of the buildings through assessing energy performance and certificate them, the EU published Energy Performance of Buildings Directive (EPBD) in 2002. This directive was revised and “cost optimum energy efficiency” concept was presented within the scope of EPBD-recast (EPBD 2010/31/EU) that has become valid by the revision of EPBD in 2010. The recast of the Directive introduced a comparative methodological framework for calculating cost optimal levels of minimum energy performance requirements. Furthermore, in all EU countries, it has been obliged to calculate the cost optimum energy efficiency levels of buildings by this recast directive. According to the methodological framework in this directive, the reference buildings of each country should be defined considering national building stock. Then, the annual primary energy consumptions of these buildings should be calculated and the energy improvements measures should be defined in order to develop the energy performance of these buildings. Finally, the global costs of these buildings should be assesed during the buildings’ economic life taking into account the economic indicators by sensitivity analyzes.

According to EPBD 2010/31/EU, the energy efficiency will be increased in the Union so as to achieve the objective of reducing by 20% the Union’s energy consumption and allover the greenhouse gas emmisions will be at least 20% below 1990 levels by 2020. Therefore, the percentage of energy from renewable sources in the total energy consumption will be increased. Turkey is a candidate country for the membership of EU and should perform the obligations explaned in this directive. That’s why, National Energy Efficiency Action Plan was prepared by Turkey in 2017 targeting energy savings in buildings and services, energy, transport, industry and technology and agriculture. With this plan, the energy consumption will be reduced until 2023 by enhanging percentage of renewable energy sources in Turkey.

Therefore, in order to adapt this methodology in this directive, a group of Ph.D student from Istanbul Technical University (ITU) were began to study on the national research project which is entitled “Determination of Turkish Reference Buildings and National Method for Defining Cost Optimum Energy Efficiency Level

of Buildings" supported by The Scientific and Technological Research Council of Turkey (TUBITAK) in Turkey in 2013. When the research was completed in 2015, it was decided that further study should be performed in order to increase the energy improvement of high-rise luxury residential buildings in Turkey. This thesis study was improved considering this result of the national research.

In this national research, Istanbul climate region was selected due to presence of many different building typhologies to define and collect the building parameters affecting the energy performance. Considering the existing and new buildings, the density of residential buildings is higher than the other types of buildings in Istanbul, so the residential buildings were evaluated in this research. Besides, the Directive suggests starting from residential buildings. The three residential building types were defined for the reaearch by utilizing of TUIK (Turkish Statistical Institute) data related to building stock: single family houses, standard apartments, luxury high-rise residential buildings. Then, energy performances of these buildings were analyzed and determined their current energy performance. Accordingly, the retrofit measures were developed to improve the their current energy performances then the global costs of these renovated buildings which includes initial investment, maintenance, running, energy costs and etc… were calculated during the economic life of building as specified in EPBD-recast. Finally, cost optimum energy efficiency level of these renovated buildings was determined by comparing the results of energy performances and global costs simultaneously. Looking at the results, it was seen that the energy performance of luxury high-rise residential buildings has changed unexpectedly compared to other residential building types.

The luxury high-rise residential buildings have become popular in cities in which lives upper-middle and upper income groups in the world. However, these buildings' construction and operation require great energy and generate significant amounts of carbon emission and air pollution that contribute to global warming. They consume lots of steel and cement—manufacturing these materials requires lots of energy and generates large amounts of carbon dioxide. Furthermore, these buildings' construction requires great energy and generates considerable carbon dioxide because of operating heavy machinery and equipment such as powerful cranes and pumps (e.g., pumping water and concrete to upper floors) and dump trucks. Further, the luxury high-rise residential buildings consume great energy and generate significant greenhouse emission resulting from running mega electrical, mechanical, lighting, and security systems. Architects have built these kind of buildings with poor thermal performance and without natural ventilation, meaning that buildings' owners need to continuously heat and cool indoor spaces (in the winter and summer respectively) to make sure that tenants have comfortable indoor environments. As such, the energy needed to heat and cool these buildings is not only costly but also hurts the environment by generating massive carbon dioxide. Moreover, these building types are affected by wind loads more than single family houses and apartments due to their extreme height so there are no operable windows in these buildings to protect the occupants from variable wind effect and air pressure. As a result, the ventilation of these buildings is not possible via natural ventilation. Therefore, the mechanical ventilation systems are designed for these buildings in order to meet the required fresh air for occupants. When the investment cost of mechanical ventilation system is added to other conditioning systems costs of these buildings, the heating, ventilation and air-conditioning (HVAC) system investment cost of luxury high-rise residential buildings become higher compared to other residential building types.

According to results of TUBITAK research, the standard retrofit measures were suitable and adequate for increasing the energy performance of single family houses and standard apartments. However, these measures were not sufficient to increase the energy performance of luxury high-rise residential building typology in this research and the increasing of energy improvement of this building type was not as high as single family houses and standard apartments. Therefore, in this thesis research, it is aimed to improve the energy efficiency of the luxury high-rise residential buildings, which are usually one part of the complex buildings'group, by reducing the energy usage of HVAC and DHW (Domestic Hot Water) systems throughout utilizing of the renewable energy systems and lost thermal energy of the buildings in the vicinity.

A very comprehensive literature survey was undertaken before this thesis research and many studies were reached that provided different methods for increasing energy performance by reducing global costs during the economic lifetimes of buildings in different countries. However, no further investigation was undertaken which the advanced energy improvement measures are developed for Turkeys' national conditions when the standard/traditional measures for luxury high-rise residential buildings are not sufficient. Accordingly, there isn't any research for increasing the energy efficiency of HVAC and DHW systems used in these buildings in Turkey by utilizing the renewable energy systems and lost thermal energy of the buildings in the vicinity considering EPBD-recast.

In this thesis research, a different method is suggested by using a new approach in order to reduce both annual primary energy consumption and global costs during the economic lifetime of the high-rise residential buildings by utilizing the renewable energy systems and the lost thermal energy of the buildings in the vicinity. In addition, it is aimed to reach the EU's 2020 targets defined in EPBD 2010/31/EU Directive and 2023 targets of Turkish National Action Plan by increasing the renewable energy portion in construction sector and recovering the thermal energy of exhaust gas of building heating systems. For this purpose, two case study buildings were chosen as reference building. The first one is an existing building, representing luxury high-rise residential buildings in Istanbul. The second one is also the same building but in this case, the amount of fresh air supplied by the mechanical ventilation system is half as much as the first one. The influence of design conditions has also been revealed on efficiency of the proposed systems in this study.

As a result, it has been seen that the advanced renovations that are applied by this new approach for reducing the annual primary energy systems and global costs of luxury high-rise residential buildings are much more efficient than standard renovations. Accordingly, this new approach will become a reference for the proposed design of HVAC and DHW systems in the luxury high-rise residential buildings in both Turkey and Mediterranean climate. These types of residential buildings are similar to commercial buildings due to being part in the same structure with the other buildings that have different usage purposes, their complex mechanical systems and the higher transparency rates compared to other residential building types. Therefore, this approach will also guide the futher researches to improve the energy efficiency of commercial buildings in Turkey.

KARMA YAPILARDAKİ YÜKSEK KATLI LÜKS KONUT BİNALARININ ENERJİ VERİMLİLİĞİNİN GELİŞMİŞ MEKANİK SİSTEMLERDEN FAYDALANARAK ARTTIRILMASI İÇİN YENİ BİR YAKLAŞIM ÖNERİSİ

ÖZET

Dünya geneline bakıldığında, artan insan nüfusu inşaat sektöründe büyük gelişmeler meydana getirmiş ve bina sayısının büyük oranda artmasına neden olmuştur. Bina sayısındaki bu artış ise gelecekte daha fazla enerji kaynağına ihtiyaç olacağı anlamına gelmektedir. Bununla birlikte, mevcut enerji kaynakları her geçen gün azalmakta ve daha fazla enerji kaynağı daha fazla CO_2 salımı anlamına gelmektedir. Binalar, Avrupa Birliği'nde (AB) enerji tüketiminin yaklaşık %40'ından ve %36 oranında CO_2 salımından sorumludur. Bu nedenle, özellikle binalarda enerji performansının iyileştirilmesi son yıllarda önemli bir konu haline gelmiştir.

Binalarda enerji verimliliğinin arttırılması ve binaların enerji sınıflarının belirlenerek sertifikalandırılması için AB tarafından 2002 yılında “Binalarda Enerji Performans Yönetmeliği” (EPBD) yayınlamıştır. 2010 yılında bu yönetmelik güncellenmiş ve yeni yönetmelik (EPBD-recast) kapsamında “maliyet optimum enerji verimliliği” kavramı ortaya konulmuştur. EPBD-recast ile Avrupa ülkelerine binalarda maliyet optimum enerji verimliliği seviyelerini hesaplama zorunluluğu getirilmiştir. Bu yönetmelikte yer alan çerçeve yönteme göre, her ülkenin referans binaları ulusal bina stoğu dikkate alınarak tanımlanmalıdır. Daha sonra, bu binaların yıllık birincil enerji tüketimleri hesaplanmalı ve bu binaların enerji performanslarını geliştirmek için enerji iyileştirme önlemleri tanımlanmalıdır. Son olarak, ekonomik göstergeler dikkate alınarak duyarlılık analizleri yolu ile bu binaların ekonomik ömürleri boyunca uzun dönem toplam maliyetleri değerlendirilmelidir.

EPBD 2010/31/EU yönetmeliğine göre, 2020 yılına kadar enerji tüketimini %20 oranında azaltmak ve sera gazı salımının tamamının 1990 seviyelerinin en az %20 altında kalmasını sağlamak amacıyla AB’nin enerji verimliliği artırılacaktır. Bu nedenle, toplam enerji tüketiminde yenilenebilir kaynaklarından elde edilen enerjinin oranı artırılacaktır. Türkiye, AB üyeliğine aday bir ülke olduğu için bu direktifte yer alan yükümlülükleri yerine getirmesi gerekmektedir. Bu nedenle, 2017 yılında Türkiye tarafından Ulusal Enerji Verimliliği Eylem Planı hazırlanarak, bina ve hizmetleri, enerji, ulaştırma, endüstri, teknoloji ve tarım alanlarında enerji tasarrufu hedeflenmiştir. Bu plana göre Türkiye'de yenilenebilir enerji kaynaklarının yüzdesi artırılarak 2023 yılına kadar enerji tüketimi azaltılacaktır.

Bunun yanında, Türkiye’de 2013 yılında İTÜ’deki bir grup doktora öğrencisi tarafından EPBD-recast’da gösterilen bu çerçeve yöntem esas alınarak “Binalarda Maliyet Optimum Enerji Verimliliği Seviyesi için Türkiye Koşullarına Uygun Yöntemin ve Referans Binaların Belirlenmesi” başlığında TÜBİTAK destekli ulusal bir araştırma projesi başlatılmıştır. 2015’te tamamlanan araştırma sonunda yüksek katlı lüks konut binalarının enerji iyileştirmesinin arttırılabilmesi için daha ileri seviye de bir çalışma yapılması gerektiğine karar verilmiştir. Bu tez çalışması, ulusal araştırmanın bu sonucu temel alınarak geliştirilmiştir.

Bu ulusal araştırmada, enerji performansına etki eden bina parametrelerinin belirlenmesi ve derlenmesi için birçok farklı bina tipolojisinin bir arada bulunması nedeniyle İstanbul iklim bölgesi seçilmiştir. Bu bölgedeki mevcut ve yeni binalara bakıldığında konut binalarının yoğunluğu diğer bina tiplerine göre daha yüksek olduğu için bu araştırmada konut binaları değerlendirilmiştir. Ayrıca, Direktif de çalışmalara konut binalarından başlamayı önermektedir. TÜİK'in (Türkiye İstatistik Kurumu) mevcut yapı stoku ile ilgili verileri kullanılarak araştırma için üç yapı tipi belirlenmiştir: tekil aile konutları, standart apartmanlar ve yüksek katlı lüks konut binaları. Daha sonra, bu binaların enerji performansları analiz edilmiş ve mevcut enerji performansları belirlenmiştir. Binaların mevcut enerji performanslarını iyileştirmek için önlemler geliştirilmiş ve sonrasında ise EPBD-recast'da belirtidiği gibi binanın ekonomik ömrü boyunca, ilk yatırım, bakım, işletme, enerji vb. maliyetlerin de içinde bulunduğu uzun dönem toplam maliyetleri hesaplanmıştır. Son olarak, yenilenen binaların enerji performanslarının ve uzun dönem toplam maliyetlerinin sonuçlarının eş zamanlı olarak karşılaştırılmasıyla bu binaların maliyet optimum enerji verimliliği seviyesi belirlenmiştir. Sonuçlara bakıldığında, yüksek katlı lüks konut binalarının enerji performansının diğer konut tiplerine göre beklenmedik bir şekilde değiştiği görülmüştür.

Yüksek katlı lüks konut binaları, dünya genelinde üst-orta ve üst gelir gruplarının yaşadığı şehirlerde popüler hale gelmiştir. Ancak bu binaların inşa edilmesi ve işletmesi büyük miktarda enerji gerektirmektedir ve küresel ısınmaya neden olan önemli miktarda karbon salımına ve hava kirliliğine sebep olmaktadır. Yüksek katlı bu binalar çok fazla çelik ve çimento tüketir ayrıca bu malzemeleri üretmek çok fazla enerji gerektirir ve çok miktarda karbondioksit üretilmesine neden olur. Ayrıca, bu yüksek binaların inşası sırasında damperli, kamyonlar, güçlü vinçler ve pompalar gibi ağır makine ve ekipmanların kullanılması nedeniyle (örneğin, su ve betonun üst katlara pompalanması) önemli miktarda enerji tüketilirken yüksek oranda da karbondioksit üretilir. Ayrıca, yapı malzemelerini uzak mesafelerden (bazen dünyanın dört bir yanından) taşımak da yüksek enerji tüketimine ve muazzam karbondioksit üretimine sebep olmaktadır. Alternatif çevre dostu malzemeler (örneğin, çelik ve betondan daha küçük ekolojik ayak izine sahip olan yerel ahşap, toprak, kil veya çakıl), yüksek katlı lüks konut binalarının inşa edilmesi için uygun değildir. Dahası, lüks yüksek katlı konut binaları gerek mekanik gerek aydınlatma gerekse de güvenlik sistemleri sebebiyle yüksek oranda elektrik tükettiği için büyük miktarda enerji tüketir ve sera gazı üretirler. Mimarların, ısıl performansı iyi olmayan ve doğal havalandırma yapılamayan yüksek katlı bu binaları inşa etmesi bina sahiplerinin konforlu iç mekânlara sahip olabilmeleri için yaşadıkları mekânları sürekli olarak (yaz ve kış mevsimleri boyunca) ısıtmaları ve soğutmaları gerekliliğini getirmiştir. Böylelikle, bu binaları ısıtmak ve soğutmak için ihtiyaç duyulan enerji sadece pahalı olmakla kalmaz, aynı zamanda çevrede de büyük miktarda karbondioksit oluşturarak çevreye zarar verir. Bunlara ek olarak, kentsel ısı adası (KIA) etkisi, yoğun şehir içi mekânlarda sıcaklıktaki artışa işaret eder. Kentsel alanlardaki ısının yoğunluğu veya KIA, sıcaklığı 10-12 Fahrenheit artırabilir. Genel olarak, aşırı ısı meydana geldiğinde, yüksek katlı binaların bulunduğu şehirler diğer yerlerden daha fazla soğumaya ihtiyaç duymakta, bu da bina alanlarını serinlemek için daha fazla enerji ihtiyacı yaratmaktadır. Ayrıca, ısı dalgaları hem iç hem de dış mekân ısıl konforsuzluğu şiddetlendirir ve insan vücudu gece serinleyemediğinde bu, insanların sağlığını olumsuz yönde etkiler. Üstelik bu yapı tipleri, aşırı yükseklikleri nedeniyle rüzgâr yüklerinden tekil aile konutlarına ve apartmanlara kıyasla fazla etkilemektedir, dolayısıyla kullanıcıları değişen rüzgâr etkisi ve hava basıncından korumak için bu binalarda genellikle açılabilir pencere bulunmamaktadır. Sonuç olarak, bu binaların havalandırması doğal havalandırma ile mümkün olmamaktadır. Bu nedenle, bina kullanıcılarının ihtiyacı olan temiz havanın karşılanması amacıyla bu binalar için mekanik havalandırma sistemleri tasarlanmıştır. Ancak, mekanik havalandırma sisteminin yatırım maliyetine bu binaların diğer iklimlendirme sistemleri maliyetleri eklendiğinde, lüks yüksek katlı konut binalarının ısıtma, soğutma, havalandırma ve sıhhi sıcak su sistemi yatırım maliyeti diğer konut yapı tiplerine göre daha yüksek olmaktadır.

TUBİTAK araştırmasının sonuçlarına göre, uygulanan standart verimlilik önlemlerinin tekil aile konutlarının ve standart apartmanların enerji performansını arttırmak için uygun ve yeterli olduğu görülmüştür. Ancak, aynı önlemlerin yüksek katlı lüks konut binalarının enerji performansını artırmakta yeterli olmadığı ve enerji kullanımındaki yıllık düşüşün tekil aile konutları ve standart apartmanlar kadar yüksek olmadığı tespit edilmiştir. Bu nedenle bu tez araştırmasında, genel olarak farklı fonksiyonlara sahip bina gruplarıyla aynı yapı içinde bulunan bulunan yüksek katlı lüks konut binlarının enerji verimliliğini arttırmak için ileri düzeyde önlemler geliştirilerek ısıtma, soğutma, havalandırma ve sıhhi sıcak su sistemlerinin enerji kullanımını gerek yenilenebilir enerji sistemlerini gerekse binalardan meydana gelen kayıp ısı enerjileri geri kazanımından faydalanarak azaltılması hedeflenmiştir.

Bu araştırmaya başlamadan önce oldukça geniş kapsamlı bir kaynak araştırması yapılmış ve farklı ülkelerdeki binaların uzun dönem toplam maliyetlerini azaltarak enerji performansını arttırmaya yönelik farklı yöntemlerin sunulduğu çalışmalara ulaşılmıştır. Ancak Türkiye iklim şartlarındaki yüksek katlı lüks konut bina tipleri için uygulanan iyileştirme önlemlerinin yeterli olmadığı durumda ileri düzey iyileştirme önlemlerinin geliştirildiği ve binanın ısıtma, soğutma, havalandırma ve sıhhi sıcak su sistemlerinin enerji verimliliğini yenilenebilir enerji sistemlerinden ve binalardan meydana gelen kayıp ısı enerjisinin geri kazanımından faydalanarak arttırıldığı herhangi bir araştırmaya ratlanmamıştır.

Bu tez araştırmasında sunulan yaklaşımda, karma yapı içinde bulunan yüksek katlı lüks konut binlarında kullanılan mekanik tesisat sistemlerinin tükettiği enerjinin hem yenilenebilir enerji sistemlerinden hem de çevredeki binaların kayıp ısı enerjilerinin geri kazanımından faydalanarak azaltılması ve bu yolla binanın ekonomik ömrü boyunca maliyetlerinin düşürülmesi adına farklı bir yöntem önerilmektedir. Ayrıca bu yeni yöntemde, binalarda yenilenebilir enerji kaynaklarının kullanım oranının arttırılması ve her yıl binaların ısıtma sistemlerinin bacalarından atılan kayıp ısı enerjinin geri kazanımı hedeflenmektedir. Böylece gerek AB'nin EPBD 2010/31/EU direktifinde tanımlı 2020 hedefleri gerekse Türkiye'nin bu direktife göre geliştirdiği Ulusal Eylem Planı'nda yer alan 2023 hedeflerine ulaşabilmesi için bir yöntem önerisi sunulmaktadır. Bu amaçla, araştırma için 2 adet referans bina seçilmiştir. Birincisi, İstanbul'da yüksek katlı lüks konut binalarını temsil eden mevcut bir binadır. İkinci bina da aynı binadır; ancak binanın mekanik havalandırması, Binalarda Isı Yalıtım Kuralları Standardı'nda (TS 825) konutlar için belirlenmiş olan taze hava oranına bağlı olarak yeniden tasarlanmış ve birinci binanın toplam taze hava miktarının yarıya düşürüldüğü bir bina haline getirilmiştir. Böylece, bu çalışmada önerilen sistemlerin verimliliğinde tasarım koşullarının da etkisi ortaya konulmuştur.

Sonuç olarak, binanın ısıtılması, soğutması, havalandırılması ve sıhhi sıcak su ihtiyacı için önerilen sistemlerin yüksek katlı lüks konut binalarının yıllık birincil enerji tüketiminin düşürülmesinde standart/geleneksel önlemlerden çok daha verimli olduğu görülmüştür. Bununla birlikte önerilen bu yeni yöntem gerek Türkiye'deki gerekse Akdeniz iklimindeki konut binalarının mekanik sistem tasarımı için bir referans olacaktır. Bu konut tipi gerek farklı kullanım amaçlarına sahip binalarla aynı yapı içinde bulunması gerek karmaşık yapıdaki mekanik sistemleri gerekse diğer konut tipleriyle kıyaslandığında saydamlık oranının daha yüksek olması nedeniyle ticari binalara da benzerlik göstermektedir. Bu nedenle, bu araştırma neticesinde elde edilen yeni yaklaşım ile gelecekte Türkiye'deki ticari binaların enerji verimliliğinin arttırılması için yapılacak olan çalışmalara da rehberlik edecektir.

1. INTRODUCTION

This thesis research aims to define the cost optimum energy efficiency level of luxury high-rise residential buildings located in a complex buildings' group in Turkey by basing on the comparative methodology framework explained in the recast version of the Energy Performance of Buildings Directive (EPBD-recast). This study focuses on reducing both primary energy consumption and global costs of these buildings by proposing advanced heating, cooling and air-conditioning (HVAC) system components that will lead Europian Union's (EU) 2020 and Turkey's 2023 renewable energy targets. Accordingly, this thesis study discuss the heat recovery of the flue gas that will improve the boiler efficiency, save fuel, and can be utilized for heating of occupied spaces and obtaining of domestic hot water (DHW). This thesis reseach has an important role in terms of reducing dependence on foreign energy sources of Turkey and supporting national development by approaching advanced HVAC retrofits instead of standart HVAC retrofits.

1.1 Purpose of Thesis

In order to improve the energy efficiency of the buildings through assessing energy performance and certificate them, the European Union published Energy Performance of Buildings Directive (EPBD) in 2002 [1]. Within the harmonization procedure of EU legislations in Turkey, Building Energy Performance Regulation was published in 2008 and with this regulation it has been required to give energy certificate to every building by using BEP-tr calculation method [2, 3]. During this process in Turkey, there have been new developments in EU countries and "cost optimum energy efficiency" concept is presented within the scope of EPBD-recast that has become valid by the revision of EPBD in 2010. By this recast directive, in all EU countries, it has been obliged to calculate the cost optimum energy efficiency levels of buildings [4]. It is required that related calculations based on the frame which has been published by European Commission on January 2012. The recast version of the Energy Performance of Buildings Directive establishes that Member

States (MS) must ensure that minimum energy performance requirements are set with a view to achieving cost-optimal levels. This is defined as the energy performance level, which leads to the lowest cost during the estimated economic life-cycle. Furthermore, the recast of the Directive introduced a comparative methodological framework for calculating cost-optimal levels of minimum energy performance requirements. Specifically, the cost-optimal methodology, defined in detail by EU Guidelines, allows evaluating the energy and economic effectiveness of different energy efficiency measures/packages/variants, which represent different retrofit scenarios. The application of this methodology represents the junction between the energy and environmental sustainability with the economic effectiveness [5]. In Figure 1.1, the timeline of EPBD is illustrated from the publication to 2020 target of EU.

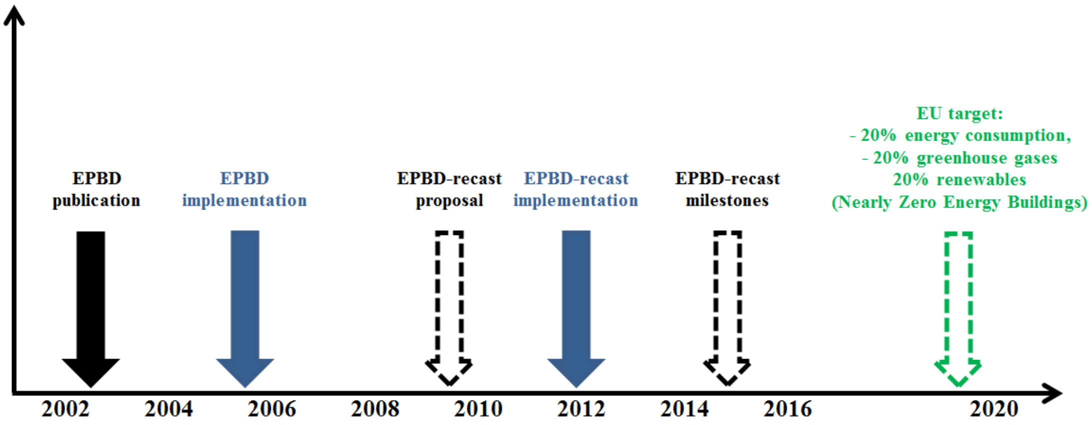

Figure 1.1 : Timeline of the EPBD and its implementation [6].

According to Directive 2010/31/EU, the buildings account for 40% of total energy consumption in the Union. The sector is expanding, which is bound to increase its energy consumption. Therefore, reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce the Union’s energy dependency and greenhouse gas emissions. Together with an increased use of energy from renewable sources, measures taken to reduce energy consumption in the Union would allow the Union to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). The European Council of March 2007 reaffirmed the Union’s commitment to the Union-wide development of energy from renewable sources by endorsing a mandatory target of a 20% share of energy from renewable sources by

2020. Directive 2009/28/EC establishes a common framework for the promotion of energy from renewable sources [4].

Directive 2010/31/EU defines the nearly zero-energy building (nZEB) as a building that has a very high-energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. Therefore, MB shall include measures/packages/variants necessary to meet the minimum energy performance requirements for nearly zero-energy buildings defined by Article 9 of Directive 2010/31/EU for achiving 2020 targets.

The methodology of this thesis bases on the developments in the field of reducing energy consumption of the buildings in both EU and Turkey. Therefore, the energy regulations and legal measures published from the beginning of 2002 are explained in order to increase the energy efficiency of the buildings in EU and Turkey in this thesis study. Besides, the studies are also included for increasing the energy performance of buildings in Turkey during these developments in EU. The unique idea of this thesis study directly sourced from the results of the TUBITAK project that is a project for adaptation of the methodology framework in EPBD 2010/31/EU for nZEB concept to Turkey. In the conclusion, the comprehension of the improvements is a key point for understanding of the purpose and importance of this thesis study.

In this thesis study, the target is improving the cost optimum energy efficiency level of luxury high-rise residential buildings in Turkey by supporting the HVAC systems of these buildings via the utilization of renewable energy systems and heat recovery of lost thermal energies of buildings in the vicinity. Within the scope of thesis, it was considered that, these complex and large residential building types should not be evaluated as a single structure because these buildings are large, complex and multi-story buildings and residence types are one of the parts in complex buildings' group. In addition, the required thermal comfort and indoor air quality in these residential types higher than the other residential building types (single family houses and apartment buildings) so the annual energy consumption is also quite high in luxury high-rise residential buildings [7]. In order to ensure the high indoor climate and thermal conditions, the high investment costs are required for the HVAC systems of these buildings and these systems consume high energy independently from the climate zones, local resources and socioeconomic factors of the countries generally. Therefore, the running, maintenance and energy costs of these systems are also notably high during the year. As a result, the contractors and occupants continue to spent a good deal of money on the HVAC systems of luxury high-rise residential buildings that are too expensive in terms of initial investment cost, annual cost and the annual energy consumption compared to other residential building types across the country.

On the other hand, the interactions of these residential buildings with the other occupied areas that are offices, shopping malls, fitness and social facilities in these building will not be able to ignore. Therefore, it is considered that, thermal and energy interactions between residence units and other occupied areas should be included in studies in the scope of this thesis research. Moreover, the interactions between these buildings and other buildings around them should be analyzed considering sunshine duration and shading effects and their influences on energy demand and consumption of the buildings should also be investigated in the scope of this thesis research.

Therefore, the obtaining of national standards and boundary conditions for these building types in Turkey is aimed through determining optimum levels of global costs for HVAC systems to be used and improving energy efficiency of these building types. For this purpose, the scope of this thesis is to offer a new approach to improve the energy efficiency level of luxury high-rise residential buildings located in a buildings complex that included building types with different functions. In order to develop this new approach the advanced improvement measures should have to be tested through the energy performance calculations for case study buildins as outlined below:

- Determination of case study buildings that represents the luxury high-rise residential buildings in a selected pilot region,
- Calculation of annual primary energy consumption of case study buildings,
- Determination of retrofit measures applied to case study buildings,
- Calculation of annual primary energy consumption of renovated buildings by applying retrofit measures,

- Calculation of global costs,
- Making relevant sensitivity analyzes for the financial data used in the analyzes,
- Identification of cost-optimum energy efficiency level for luxury high-rise residential building.

As a result, the national methodology will be developed for determining cost optimum energy efficiency level of luxury and high-rise residential buildings in this thesis research. These studies will be valuable resources for the studies about these kinds of buildings in other pilot region. Using this methodology, the cost optimum energy efficiency levels can be determined for different climate zones selecting new pilot region. Besides, turning these high-energy consuming buildings into more energy efficient buildings by improving their energy performance without compromising thermal comfort levels and the saving the energy resources and economic interests of the country is the other importance of this thesis.

1.2 Literature Review

Looking at the worldwide, the building quantity rises gradually due to increasing human population so that more energy resources will be needed in the future. However, current energy resources are reducing day by day, and more energy resources mean more CO_2 emissions [8]. Buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU [9]. Accordingly, the buildings are one of the highest energy consumption sectors in the world that declared by International Energy Agency (IEA) as shown in Figure 1.2 below.

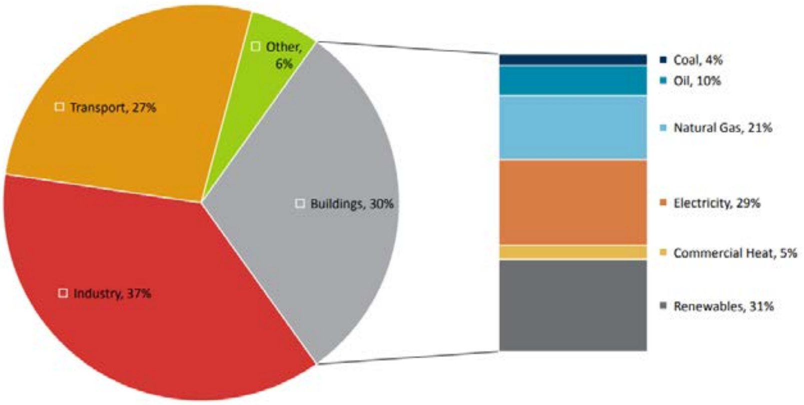

Figure 1.2 : Final energy consumption by sector and buildings energy mix, 2013 [10].

Therefore energy saving become important issue especially in the buildings. In order to prevent the increasing of these ratios in the future, the description of energy efficient building design comes into prominence for supplying the necessary energy demand and choosing the suitable and effective HVAC systems according to building typology.

Working on energy efficiency in buildings has been going on for years. Measures for energy conservation have started to be taken from the traditional settlements and the buildings have been constructed considering the climatic conditions. In parallel with the technological developments recorded in the years, the developments in the energy systems have been realized and the user comfort has been provided through these systems and the energy conservation in the buildings has been taken into the second plan. However, the oil crisis of the 1970s shows that the energy obtained from non-renewable sources must be used with care and from these dates the work has been given to the whole world on energy efficiency issues. Economic analyzes are also included in the research. For example, studies on cost-effective energy efficiency in building design in the United States began in the late 1980s [11]. In addition to studies and analyzes on energy efficiency in buildings, buildings/values to be referenced in building energy efficiency and the first examples of building categorization are found in the late 1980s. One of the first studies to categorize buildings is to determine reference building categorization for the United States. In this study by Briggs et al., Mainly commercial buildings were considered and the effect of the physical variables such as size, year of construction and location of the building on the energy load of the building was investigated. Categorized by a limited number of building categories, the categories are defined to reflect the diversity of the building site and to represent all commercial buildings as much as possible [12]. In 2005, the United States Department of Energy (DOE) created a series of commercial reference buildings called the "Commercial Benchmark" for the United States. The reference buildings that are constructed include existing and new buildings that represent the building site for both before and after 1980. In this study, the identified reference buildings are explained by detailed charts including the building description, the values of the parameters and the source of the data, as well as the energy models of these buildings for use in the EnergyPlus simulation tool and these information are constantly updated [13].

The first version of the EPBD, published in 2002 and put into practice in 2003, required the development of methods that comply with EU legislation and standards in order to calculate the energy performances of buildings and to determine the energy performance levels of the buildings with this method. It also requires compulsory certificates showing the energy performance classes of buildings to be created for each building, and these certifications must be available for sale and lease of buildings [1]. Although the first version of the EPBD mentions that energy efficiency investments are cost-effective, there is no explanation as to how this should be assessed and which studies should be undertaken. With the revision in 2010, the EPBD has been renewed and re-published with the EPBD-recast name [4]. The revised directive obliges all EU countries to determine the minimum energy performance requirements on the basis of an optimal level of cost. The cost has also been announced by the EU as a framework to be monitored for the determination of optimum energy efficiency levels. This framework method has been published under the EU directive to support the EPBD-recast in 2012. This method consists of six main steps leading to the determination of cost optimum energy efficiency levels. This method, which each country must adhere to on its own terms, consists of the following main steps:

- Identification of national reference buildings
- Determination of energy efficiency measures/measure packages
- Calculation of energy consumption in terms of primary
- Calculation of total costs
- Making relevant sensitivity analyzes for the financial data used in the analyzes
- Determination of optimum cost level for energy performance of each reference building

Furthermore, considering existing building stock, it is obvious that cost optimum level could not be calculated for each building separately. Due to this fact, as a first step it is necessary to define the reference buildings which represent the building stock in the best way and to adopt large scale actions based on these buildings' analysis. Through this aim, it is compulsory to determine the most representative reference buildings for both new and existing buildings as stated in the last EPBD [14].

In order to calculate energy efficiency of the buildings according to the cost-optimal methodology in EPBD-recast, the energy performance modeling of the buildings are carried out by using the building simulation tools generally. Building energy performance modeling, as a decision making process on building architecture and system design, includes several segments according to the parameters taken into consideration and scale of assessment. Over the last decade, there is a respectable rise about the involvement of building energy performance simulation (BEPS) tools in building design process through scientifically developed modules by energy demand and consumption calculations, thermal and visual comfort analysis and valuation of emission rates. Wide ranges of users from different disciplines use BEPS tools related with their specialty. BEPS tools give users significant foresight, comparison and performance evaluation with various options during early-design, design and operation phases. To ensure the energy efficient design in buildings, energy performance simulations should be performed in the beginning of the design process and continue until the construction process [8]. There are many building simulation tools have been developed by the energy department of countries and software companies from the beginning of 1970’s. These tools have been still updated year by year according to changing user requirements, structural and mechanical system complexity, climatic factors and energy policies. Among these tools, the simulation tools that use detailed dynamic calculation methodology have come to the forefront. EnergyPlus and DesignBuilder are among building simulation tools that use this methodology.

EnergyPlus is a comprehensive building energy performance modeling tool that emerged in the early 1970’s with the merger of two important programs, such as DOE-2 and Building Loads Analysis and System Thermodynamics (BLAST), which began to develop in the United States of America (USA), and is still being developed today at the Lawrence Berkeley Laboratory in USA [15]. Using EnergyPlus, design and analysis of facade systems, artificial lighting and daylighting design, thermal and visual comfort analysis, thermal load calculation, design and analysis of conditioning systems, renewable and district energy system design, carbon emissions and building energy costs and more can be done using detailed dynamic method. In addition to this, it is possible to make a green building design with EnergyPlus by creating a detailed building model and it is possible to make energy modeling suitable for voluntary certification programs such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) and to obtain the desired output as a result file. EnergyPlus can calculate the building's heating-cooling loads using algorithms such as transfer function, finite difference and finite elements. It calculates annual (for 8760 hours) using detailed dynamic calculation method. These calculations are made using the hourly climate data. This software is an open-source free software, well-known in academic and commercial contexts for dynamic simulations and good enough in terms of capabilities [16].

The other detailed-dynamic building simulations tool is DesignBuilder which performs all of the energy analyzes by using the EnergyPlus infrastructure. DesignBuilder is a United Kingdom (UK) based building simulation tool that can be used to model all buildings with user friendly interface. With using DesignBuilder, it is possible to design heating, cooling and ventilation systems, natural ventilation, thermal comfort and daylight analysis, annual energy consumption, CO_2 emission and cost analysis, building energy performance analysis according to LEED, energy optimization and Computational Fluid Dynamics (CFD) analysis. This tool is also performing the daylight analysis using the infrastructure of the Radiance lighting simulation tool. The building data such as The Green Building XML Schema (gbXML) and Drawing Exchange Format (DXF) format can easily be imported into DesignBuilder from Building Information Modeling (BIM) programs such as Revit and ArchiCAD. The most important feature that distinguishes DesignBuilder from EnergyPlus is its user-friendly interface. Architectural and mechanical modeling, building energy performance and conclusion of the analysis are carried out very fast and simple without the need of any other programs. DesignBuilder is a licensed program and the modules of the current version of the program can be purchased individually or in packages.

In order to determine the cost-optimum energy level of the building using these tools, the architectural, structural, mechanical and electrical design must be carried out efficiently considering climate, topography, materials, lighting system, HVAC system efficiencies, etc… Therefore, the energy efficient building design comes into prominence. The energy efficient design of buildings is definitely a strong weapon that we must use in order to fight for a sustainable development and for a green world [17]. However, it is an extremely complex issue that involves several decision variables, such as the sundry characteristics of building envelope and HVAC systems, and objective functions, such as the minimization of energy consumption [18], financial expenditure [19], polluting emissions [20] and indoor thermal discomfort [21]. Therefore, the architects, civil engineers, mechanical engineers, electric engineers should work together during the design process as design team. Each group should be aware of that, constructing a building is to constitute an interacted system to the environment which it will be stand and it will be affected by seasonal and daily climatic changes [1]. For constructing the energy efficient building, integrated design is very important process and the design teams should work collaboratively from the beginning of the design process to the end.

In the beginning of the design, physical properties as building geometry, orientation, façade transparency rates, opaque and transparent components, shading elements, interior layout, thermal zones and obstacles around the building that affect the energy performance of buildings should be determined. Secondly, thermo physical properties as heat conductivity coefficient, density and specific heat of opaque components of the building envelope and the solar heat gain coefficient, daylight transmittance values and the overall heat transfer coefficient of transparent components of the building envelope and infiltrations that are important parameters for determining the building heating and cooling loads should be decided. Besides, illuminance level, loads and efficiency of lighting equipment are also important for energy efficiency and occupancy comfort. After determining these passive system parameters, the building HVAC equipment with appropriate capacity and efficiency should be chosen working with building automation system. All these parameters should be tested together in order to ensure the energy efficient design. For that reason, the crucial benefits of building energy performance modeling and simulation tools and consultancy on measurements to increase the building energy efficiency are being considered among building design teams [22].

One of the limited numbers of researches in this recent field, which has gained importance in recent years, has been done by Corgnati and others, and these are the studies which question the current situation at the international level by introducing the reference building concept [23]. In addition to the studies on the international scale and on the national scale, the processes related to the determination of reference buildings and cost optimum levels have been carried out. For example, a research was conducted in 2008 by Hernandez et al. [24], which examined the determination of reference values and energy performance levels in non-residential buildings through a field study on primary school buildings in Ireland. In 2011, a research focusing on the identification of reference office buildings, which Fabrizio E. and others have implemented, is presented. In this study, a reference building model for a large-scale office building was developed by compiling and compiling information on building stock in Italy [25]. In a research conducted in Egypt in 2012, new energy standards were examined on two housing reference buildings and cost and energy efficiency analyzes were carried out [26].

Referring to Turkey, a group of Ph.D students under the leadership of Prof. Dr. A. Zerrin Yilmaz from Istanbul Technical University (ITU) began to study on the research project to determine reference buildings for residential building types in Turkey in 2013. In the direction of EPBD, the research project supported by TUBITAK was developed which is entitled “Determination of Turkish Reference Buildings and National Method for Defining Cost Optimum Energy Efficiency Level of Buildings” in order to determine reference buildings in Turkey using the methodology that was improved according to national conditions. To determine the reference buildings, all the parameters affecting the energy performance of these buildings in pilot region (Istanbul) were determined primarily. Then, a database was obtained using these parameters representing building stock for categorizing reference buildings. Then, energy performances of these buildings were analyzed and determined their current energy performance. Finally, the improvement packages were developed to improve the current energy performances of these buildings then cost optimum energy efficiency levels of these buildings were determined analyzing the results of energy performances and costs obtained with these improvement packages.

Besides these researches, the studies have been also done on determining cost-optimum energy level of the new construction and existing buildings. These studies have been carried out determining energy efficiency measures/packages for the passive systems (construction materials, artificial and daylighting systems, shading elements…), the mechanical systems (system efficiencies, renewable and district energy systems, automation systems…) and both passive and mechanical system of the buildings. A research was conducted in 2013 by Carol et al. [27], which is optimizing hybrid ventilation in public spaces of complex buildings such as hospitals and laboratories require intensive ventilation and cooling loads with different hybrid ventilation strategies considering energy savings, occupant comfort and indoor-air quality. Another study presents different cost optimal solutions of building and technical systems for nZEBs in Italy combining with insulation materials and photovoltaic (PV) systems for a single family house published in 2015 [28]. The other research was carried out by Cristina et al. [29] considering the cost-optimal methodology for the energy retrofit of an ex-industrial building located in Northern Italy which was published in 2016. The research activity here presented aims at testing the cost-optimal methodology to support energy retrofit projects starting from an early design stage. Mohammadhossein et al. was used cost-optimal methodology for limiting domestic energy demand growth in Iran according to energy efficiency policies set by Iranian government. In this regard, it was proposed various solutions to investigate the feasibility of improving the performance of an existing typical multi-family building in Iran considering different envelope thermal insulation, shading system, window types and highly efficient systems in addition to the solar renewable energy source [30]. A new comprehensive approach was proposed by Fabrizio et al. to support cost-optimal design of building envelope's thermal characteristics and HVAC systems in presence of a simulation-based model predictive control (MPC) for heating and cooling operations. The cost-optimal solution was identified through a main mono-objective genetic algorithm (GA) that minimizes global costs for space conditioning [31].

2. PROGRESS IN THE FIELD OF BUILDING ENERGY EFFICIENCY IN EUROPEAN UNION AND TURKEY

This thesis research focuses on defining of cost-optimum energy efficiency level of luxury high-rise residential buildings in Turkey. The main source of this study depends on the results of TUBITAK research project that is a project for adaptation of the methodology framework in EPBD 2010/31/EU for nZEB concept to Turkey. Therefore, it is crucial to explain the developments in detail in order to understand the reason and the base of this thesis study. Thus, each progress in the field of building energy efficiency that occurred in both EU and Turkey is explained in detailed below.

2.1 Progress in EU in Building Energy Efficiency and Policies

With regard to the international efforts to reduce the growing energy consumption, it is highly remarkable that the building sector has an important role due to its responsibility for more than 40% of global energy used, and approximately one third of global greenhouse gas emissions, in both developed and developing countries [32]. Looking at EU, buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU. Improving the energy efficiency of buildings can also generate other economic, social and environmental benefits. Better performing buildings provide higher levels of comfort and wellbeing for their occupants and improve health by reducing illnesses and deaths caused by a poor indoor climate. The energy performance of buildings also has a major impact on the affordability of housing and energy poverty. Energy savings and efficiency improvement of the housing stock would enable many households to escape energy poverty [9]. Therefore, reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce the Union’s energy dependency and greenhouse gas emissions. One of the most important is the Energy Performance Buildings Directive (EPBD), which was developed and will be implemented with following milestones [33]:

- Dec 2002: EU adopts Energy Performance Buildings Directive (EPBD) EPBD 2002,
- Jan 2006: Deadline for transposing directive into national law,
- Nov 2008: Commission proposes revision of EPBD (EurActiv 14/11/08),
- Apr 2009: Parliament adopts first-reading position (EurActiv 24/04/09),
- Nov 2009: EU reaches political agreement on directive (EurActiv 18/11/09),
- May 2010: Parliament approves new legislation,
- May 2010: EU adopts (approves) the recast (revised) EPBD 2010 EPBD Directive 2010/31/EU on the energy performance of buildings,
- End 2018: Public buildings to have to be nearly zero energy standards,
- End 2020: All new buildings to be nearly zero energy.

2.1.1 Directive 2002/91/EC (EPBD)

The objective of this Directive is to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. The requirements are listed below according to “Annex I” in this directive [34].

This Directive lays down requirements as regards:

a) the general framework for a methodology of calculation of the integrated energy performance of buildings;

b) the application of minimum requirements on the energy performance of new buildings;

c) the application of minimum requirements on the energy performance of large existing buildings that are subject to major renovation;

d) energy certification of buildings; and

e) regular inspection of boilers and of air-conditioning systems in buildings and in addition an assessment of the heating installation in which the boilers are more than 15 years old.

The common calculation methodology should include all the aspects which determine energy efficiency and not just the quality of the building's insulation. This integrated approach should take account of aspects such as heating and cooling installations, lighting installations, the position and orientation of the building, heat recovery, etc. The minimum standards for buildings are calculated on the basis of the above methodology. The Member States are responsible for setting the minimum standards [35].

The Directive concerns the residential sector and the tertiary sector (offices, public buildings, etc.). The scope of the provisions on certification does not, however, include some buildings, such as historic buildings, industrial sites, etc. It covers all aspects of energy efficiency in buildings in an attempt to establish a truly integrated approach. The Directive does not lay down measures on moveable equipment such as household appliances. Measures on labeling and mandatory minimum efficiency requirements have already been implemented or are envisaged in the Action Plan for Energy Efficiency [35].

Energy performance certificates should be made available when buildings are constructed, sold or rented out. The Directive specifically mentions rented buildings with the aim of ensuring that the owner, who does not normally pay the charges for energy expenditure, should take the necessary action. Furthermore, the Directive states that occupants of buildings should be enabled to regulate their own consumption of heat and hot water, in so far as such measures are cost effective. The Member States are responsible for drawing up the minimum standards. They will also ensure that the certification and inspection of buildings are carried out by qualified and independent personnel. The Commission, with the assistance of a committee, is responsible for adapting the Annex to technical progress. The Annex contains the framework for the calculation of energy performances of buildings and the requirements for the inspection of boilers and of central air conditioning systems [35].

The Directive forms part of the Community initiatives on climate change (commitments under the Kyoto Protocol) and security of supply (the Green Paper on security of supply). Firstly, the Community is increasingly dependent on external energy sources and, secondly, greenhouse gas emissions are on the increase. The Community can have little influence on energy supply but can influence energy demand. One possible solution to both the above problems is to reduce energy consumption by improving energy efficiency. Energy consumption for buildings-related services accounts for approximately one third of total EU energy consumption. The Commission considers that, with initiatives in this area, significant energy savings can be achieved, thus helping to attain objectives on climate change and security of supply. Community-level measures must be framed in order to deal with such Community-level challenges. This Directive is a follow-up to the measures on boilers (92/42/EEC), construction products (89/106/EEC) and Specific Actions for Vigorous Energy Efficiency (SAVE) programme provisions on buildings. Though there is already a directive on the energy certification of buildings (Directive 93/76/EEC repealed by Directive 2006/23/32/EC), it was adopted in a different political context before the Kyoto agreement and the uncertainties with the security of energy supply in the Union. It does not have the same objectives as Directive 2002/91/EC. The latter is an additional instrument, proposing concrete action to fill any existing gaps [35].

2.1.2 Directive 2010/31/EU (EPBD-recast)

On 19 May 2010, a recast of the Energy Performance of Buildings Directive was adopted by the European Parliament and the Council of the European Union in order to strengthen the energy performance requirements and to clarify and streamline some of the provisions from the 2002 Directive it replaces [36]. This new directive is named EPBD-recast which promotes the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. The requirements are listed below according to “Annex I” in this directive [37]

a) the common general framework for a methodology for calculating the integrated energy performance of buildings and building units;

b) the application of minimum requirements to the energy performance of new buildings and new building units;

c) the application of minimum requirements to the energy performance of:

    i. existing buildings, building units and building elements that are subject to major renovation;

    ii. building elements that form part of the building envelope and that have a significant impact on the energy performance of the building envelope when they are retrofitted or replaced;
    iii. technical building systems whenever they are installed, replaced or upgraded;

d) national plans for increasing the number of nearly zero energy buildings;

e) energy certification of buildings or building units;

f) regular inspection of heating and air-conditioning systems in buildings; and

g) independent control systems for energy performance certificates and inspection reports.

The Commission should lay down a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements. Member States should use this framework to compare the results with the minimum energy performance requirements which they have adopted.

In accordance with the Directive cost-optimal level means the energy performance level which leads to the lowest cost during the estimated economic lifecycle, where [37]:

a) the lowest cost is determined taking into account energy-related investment costs, maintenance and operating costs (including energy costs and savings, the category of building concerned, earnings from energy produced), where applicable, and disposal costs, where applicable; and

b) the estimated economic lifecycle is determined by each Member State. It refers to the remaining estimated economic lifecycle of a building where energy performance requirements are set for the building as a whole, or to the estimated economic lifecycle of a building element where energy performance requirements are set for building elements.

At the next page, the curve that is analyzed the global cost and annual primary energy consumption simultaneously is illustrated in Figure 2.1. With this curve, the cost optimum efficiency level of the building is determined which leads to the lowest cost during the estimated economic lifecycle.

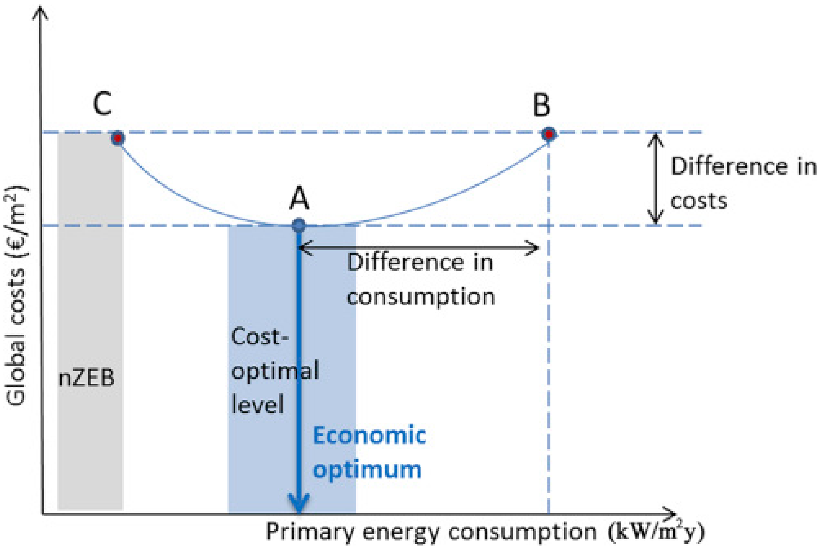

Figure 2.1 : Global cost curve (A = economic optimum, B = requirement in force, C = cost neutral compared to requirement in force) [38].

According to Article 2, a nZEB is a building that “has a very high energy performance with a low amount of energy required covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” [38]. Therefore, the concept of cost-optimal level is defined that is the energy performance level which leads to the lowest cost during the estimated economic lifecycle.

The comparative methodology framework shall allow for taking into account use patterns, outdoor climate conditions, investment costs, building category, maintenance and operating costs (including energy costs and savings), earnings from energy produced, where applicable, and disposal costs, where applicable. It should be based on relevant European standards relating to this Directive.

The comparative methodology framework shall require Member States to:

a) define reference buildings that are characterized by and representative of their functionality and geographic location, including indoor and outdoor climate conditions. The reference buildings shall cover residential and non-residential buildings, both new and existing ones,

b) define energy efficiency measures to be assessed for the reference buildings. These may be measures for individual buildings as a whole, for individual building elements, or for a combination of building elements,

c) assess the final and primary energy need of the reference buildings and the reference buildings with the defined energy efficiency measures applied,

d) calculate the costs (i.e. the net present value) of the energy efficiency measures (as referred to in the second indent) during the expected economic lifecycle applied to the reference buildings (as referred to in the first indent) by applying the comparative methodology framework principles.

At the below, the concepts including in Directive 2010/31/EU are explained in detailed to understand how the methodology framework works.

2.1.2.1 Reference building

The main objective of the use of reference buildings is to represent a typical and average housing stock in a given MS, since it is impossible to derive optimal solutions in terms of costs and energy efficiency for each building [38].

Delegated Regulation No. 244/2012 and its Guidelines defines a reference building as a "typical building geometry and systems, typical energy performance for both building envelope and systems, typical functionality and typical cost structure", being representative of a country considering its climate and geographic location [39].

Reference buildings can be obtained choosing a real or a virtual example. The first one should represent the most typical building within a specific category defined by the type of use in reference to occupancy pattern, floor area, geometrical features, thermo-physical properties of the envelope, or technical plants. The second one is a virtual building created using statistical information and surveys for each relevant parameter [38].

2.1.2.2 Energy efficiency measures

According to Directive 2010/31/EU, the energy efficiency measures are the improvements to develop the energy performance of buildings that should take into account climatic and local conditions as well as indoor climate environment and cost-effectiveness. In order to develop the energy performance of buildings, it should be reduced the amount of energy consumption of the buildings ensuring minimum energy performance requirements in new buildings and in existing buildings when buildings undergo major renovation.

2.1.2.3 Primary energy

According to Directive 2010/31/EU Article 2, primary energy is the energy from renewable and non-renewable sources which has not undergone any conversion or transformation process.

The objective of the calculation procedure is to determine the annual overall energy use in terms of primary energy, which includes energy use for heating, cooling, ventilation, hot water and lighting. According to Directive 2010/31/EU definitions, electricity for household appliances and plug loads may be included, but this is not mandatory [40].

Primary energy includes non-renewable energy and renewable energy. If both are taken into account it can be called total primary energy [40]. In order to define the primary energy consumption from non-renewable sources of a building, yearly energy demand should be multiplied to the related conversion factor. In case of renewable energy production exists, the produced energy is subtracted from the total primary energy consumption. Following equation 2.1 should be used in order to calculate the total primary energy consumption:

$$PEC_T = PEC_{nRES} - PEC_{RES} \tag{2.1}$$

Where:

- PEC_T is total primary energy consumption,
- PEC_{nRES} is primary energy consumption from non-renewable sources,
- PEC_{RES} is primary energy consumption from renewable sources,

$$PEC_{nRES} = T_f \, x \, Cf_f \tag{2.2}$$

Where:

- T_f is sum of total energy consumption of any fuel,
- Cf_f is conversion factor of any fuel.

2.1.2.4 The global cost methodology

In accordance with Annex III to Directive 2010/31/EU and Annex I (4) to the Regulation, the cost-optimal framework methodology is based on the net present value (global costs) methodology. The calculation of global cost considers the initial investment, the sum of annual costs for every year and the final value as well as disposal costs if appropriate, all with reference to the starting year. For the calculation of the macroeconomic cost optimum, the category of global costs is to be expanded by a new category, the cost of greenhouse gas emissions defined as the monetary value of environmental damage caused by CO_2 emissions related to the energy consumption in a building [40].

Besides, these costs mentioned above are categorized basically in Directive 2010/31/EU. This cost categorization for the calculation of cost-optimal levels of minimum requirements is based on standard EN 15459. It differs slightly from cost categorization systems usually used for lifecycle cost assessment (compare standard ISO 15686-5:2008 on Buildings and constructed assets - Service-life planning - Part 5 Lifecycle costing) [41]. The illustration of the cost categorization is demonstrated in Figure 2.2.

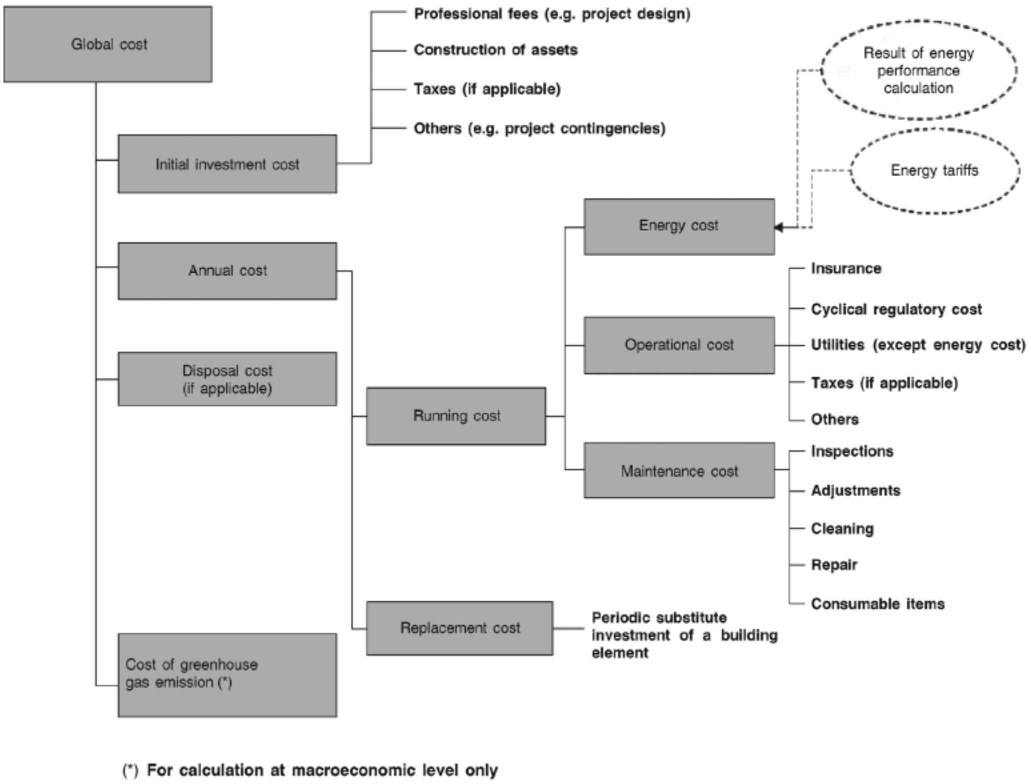

Figure 2.2 : The cost categorization according to Directive 2010/31/EU [4].

Global cost calculations result in a net present value of costs incurred during a defined calculation period, taking into account the residual values of equipment with longer lifetimes. Projections for energy costs and interest rates can be limited to the calculation period [40].

Therefore, global cost can be written as the equation 2.3,

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \times R_d(i) \right) - V_{f,\tau}(j) \right] \tag{2.3}$$

Where:

$C_G(\tau)$: Global cost referred to starting year τ_0,

C_I: Initial investment cost,

$C_{a,i}(j)$: annual cost year *i* for component *j* (including running costs and periodic or replacement costs)

$R_d(i)$: Discount rate for year *i*,

$V_{f,\tau}(j)$: Final value of component *j* at the end of the calculation period (referred to the starting year τ_0).

According to Directive 2010/31/EU Article 2, the initial investment cost means all costs incurred up to the point when the building or the building element is delivered to the customer, ready to use. These costs include design, purchase of building elements, connection to suppliers, installation and commissioning processes such as the building envelope system (insulation of building envelope, windows and doors) and building systems (heating, cooling, ventilation, domestic hot water, lighting, automation and control systems).

The equation of initial investment cost is illustrated with equation 2.4.

$$C_I = C_{I(p)} \times \left(1 + \frac{R_d(i)}{100} \right)^{\tau} \tag{2.4}$$

Where:

C_I: Initial investment cost for measure or set of measures

$C_{I(p)}$: Present value of initial investment cost

$R_d(i)$: Discount rate for year I

τ : Calculation period.

The discount rate coefficient is used to refer the replacement costs and the final value to the starting year. It is expressed as the equation 2.5:

$$R_d = \frac{1}{\left(1+R_r\right)^i} \tag{2.5}$$

Where R_r is the real interest rate and *i* is the year of calculation (e.g. *i*=15 for calculating the replacement cost of a component having a lifespan of 15 years).

The annual cost $C_{a,i}(j)$ is the sum of running costs and periodic costs or replacement costs paid in a certain year.

According to Directive 2010/31/EU, the running cost is the sum of annual maintenance costs, operational costs and energy costs. The energy costs mean annual costs and fixed and peak charges for energy including national taxes and energy costs shall reflect overall energy cost including energy price, capacity tariffs and grid tariffs. Energy costs are calculated through the following equation 2.6.

$$C_e = C_e(i) \times f_{pv}(n) \tag{2.6}$$

Where:

C_e : Energy cost

$C_e(i)$: Energy cost for year *i*

$f_{pv}(n)$: Present value factor of energy for calculation period *n*

When annual costs occur for many years, such as in case of running costs, the present value factor f_{pv} must be used, which is expressed as a function of the number of years n and the interest rate R_r as [40]. The present value factor is expressed as the equation 2.7.

$$f_{pv}(n)=\frac{\left(1+R_r\right)-1}{R_r\times\left(1+R_r\right)^n} \tag{2.7}$$

According to Directive 2010/31/EU, the operational costs mean all costs linked to the operation of the building including annual costs for insurance, utility charges and other standing charges and taxes. Maintenance costs mean annual costs for measures for preserving and restoring the desired quality of the building or building element. This includes annual costs for inspection, cleaning, adjustments, repair and consumable items.

The replacement cost is a substitute investment for a building element, according to the estimated economic lifecycle during the calculation period according to Directive 2010/31/EU. The final value $V_{f,\tau}(j)$ of a component is calculated by a straight-line depreciation of the initial investment until the end of the calculation period and referred to the beginning of the calculation period (τ = 30 years for residential and public buildings and τ = 20 years for non-residential commercial buildings).

If the calculation period τ exceeds the lifespan $\tau_n(j)$ of the considered component (j), the last replacement cost is considered for the straight-line depreciation as expressed through the following equation 2.8.

$$V_{f,\tau}(j)=V_0(j)\times\left(1+R_p\right)^{n_\tau(j)\times\tau_n(j)}\times\left[\frac{\left(n_\tau(j)+1\right)\times\tau_n(j)-\tau}{\tau_n(j)}\right]\times\frac{1}{\left(1+R_d\right)^\tau} \tag{2.8}$$

Where:

$V_0(j)$: Investment costs for component or system j (at time τ_0)

R_p: Rate of development of the price for products

$n_\tau(j)$: Number of replacements of component or system j within the calculation period

$\tau_n(j)$: Lifespan or design duration for component or system j

The last replacement cost is represented as the equation 2.9, when taking into account the rate of development of the price for products (R_p);

$$V_0(j)\times\left(1+\frac{R_p}{100}\right)^{n_\tau(j)\times\tau_n(j)} \tag{2.9}$$

The straight-line depreciation of the last replacement cost is represented as the equation 2.10 (i.e. remaining lifetime at the end of the calculation period of the last replacement of component *j* divided by the lifespan of component *j*) [42];

$$\left[\frac{\left(n_\tau(j)+1\right)\times\tau_n(j)-\tau}{\tau_n(j)}\right] \tag{2.10}$$

The discount rate at the end of the calculation period is expressed as the equation 2.11.

$$\frac{1}{\left(1+R_d\right)^\tau} \tag{2.11}$$

2.1.3 Commission delegated regulation (EU) no 244/2012

This regulation includes supplementing articles to EPBD 2010/31/EU. In consistent with Article 5 and Annexes I and III of EPBD 2010/31/EU, this Regulation fixes a comparative methodology framework to be used by Member States for calculating cost-optimal levels of minimum energy performance requirements for new and existing buildings and building elements [14].

The methodology specifies how to compare energy efficiency measures, measures incorporating renewable energy sources and packages of such measures in relation to their energy performance and the cost attributed to their implementation and how to apply these to selected reference buildings with the aim of identifying cost-optimal levels of minimum energy performance requirements. Annex III to Directive 2010/31/EU requires the Commission to provide guidelines to accompany the comparative methodology framework with the aim of enabling the Member States to take the necessary steps [14].

2.1.4 Directive 2012/27/EU

This Directive establishes a common framework of measures for the promotion of energy efficiency within the Union in order to ensure the achievement of the Unions'

2020 20% headline target on energy efficiency and to pave the way for further energy efficiency improvements beyond that date. It lays down rules designed to remove barriers in the energy market and overcome market failures that impede efficiency in the supply and use of energy, and provides for the establishment of indicative national energy efficiency targets for 2020 [43].

In this regulation, the cogeneration system is defined the significant potential for saving primary energy of high-efficiency cogeneration and district heating and cooling is also refered. According to Directive 2012/27/EU, Member States should carry out a comprehensive assessment of the potential for high-efficiency cogeneration and district heating and cooling. New electricity generation installations and existing installations which are substantially refurbished or whose permit or licence is updated should, subject to a cost-benefit analysis showing a cost-benefit surplus, be equipped with high-efficiency cogeneration units to recover waste heat stemming from the production of electricity. This waste heat could then be transported where it is needed through district heating networks.

2.2 Progress in Turkey in Building Energy Efficiency and Policies

Within the harmonization procedure of EU legislations, EPBD requirements which were published in 2002 were followed by Turkey and the national legislation was shaped in this direction in Turkey. In this context, the Energy Efficiency Law entered into force in 2007.

2.2.1 Energy efficiency law

This Law was published in 2 May 2007 in Republic of Turkey Official Gazette. The purpose of this Law is; efficient use of energy, prevention of waste, easing the burden of energy costs on the economy, and increasing efficiency in the use of energy resources and energy to protect the environment.

This Law includes the procedures and principles to be applied in the production, transmission, distribution and consumption stages of energy, industrial plants, buildings, electricity generation facilities, transmission and distribution networks, increasing and supporting energy efficiency in transportation, improving energy awareness throughout the society and utilizing renewable energy sources.

Fallowing this law, Building Energy Performance Regulation was published in 2008 in Turkey.

2.2.2 Building energy performance regulation

This Regulation was formed by basing on 5627 Energy Efficiency Law and 3194 Construction Law and EPBD 2002/91/EC. This regulation is designed to measure the minimum performance of the existing buildings including the electrical, mechanical, lighting systems and architectural solutions of the buildings by using the calculation method prepared in the framework of the relevant standards. Besides, it includes the regulation and supervision of the building energy performance certificate, the positive effects of renewable energy and cogeneration systems and the measures to increase energy efficiency so as not to damage the assets of the buildings registered as cultural assets. All the building typologies are included in this regulation except industrial buildings, buildings that will operate for less than 2 years, buildings with usage areas less than 50 m^2, greenhouses, workshops, unconditioned storages and barns [44]. The regulation also aims to create the building inventory all over the country in a short period of time and update this inventory by audits.

Under the heading of "Building Project Design and Architectural Applications in terms of Building Energy Performance" in the Building Performance Regulation Part III, the parameters such as the location and orientation of the building should be designed to increase energy efficiency by taking into consideration the sun, wind, humidity and other external conditions. Moreover, these parameters should be detailed in order to comply with Turkish Heat Insulation Requirements (TS 825) and the applicability of the use of renewable energy sources to the project needs to be investigated.

After this regulation had come into force on 5 December 2008, the building energy performance calculation method (BEP-tr) for Turkey's national conditions developed and published in 2010 in accordance with the methods prescribed by the EPBD and EN standards [45].

2.2.3 Building energy performance calculation methodology-Turkey (BEP-tr)

Building energy performance calculation method was developed in order to assess the impact on buildings energy consumption of all the inputs that have a stake in building energy expenditure compiling specific information of Turkey such as climate data, coordinate and materials. Furthermore, determining the energy performance of existing and new buildings is possible with this calculation method based on EN 13790 Standard [44].

Calculation method of Energy Performance of Buildings in Turkey includes,

a) Calculation of net energy amount required for heating and cooling of the building,

b) Determination of total heating and cooling energy consumption of the building considering the losses resulting from systems which will meet net heating and cooling energy requirement, and system efficiencies,

c) Determination of ventilation energy consumption,

d) Calculation of lighting energy requirement and consumption for time of no daylight utilization and areas where daylight is not effective by considering the effects of daylight in the buildings,

e) Calculation of energy consumption necessary for sanitary hot water [46].

Building net energy inputs and outputs included in the calculations are seen in Figure 2.3.

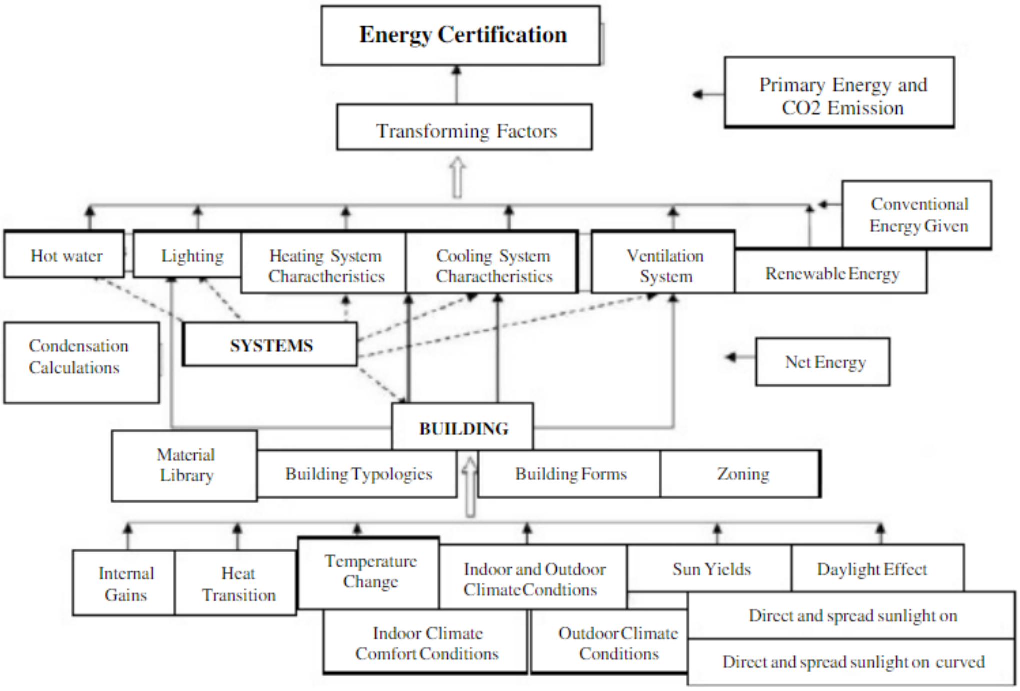

Figure 2.3 : Net energy data inputs and outputs [46].

Prof. Dr. A. Zerrin YILMAZ coordinated the team that developed the net energy module of this calculation method and has published and presented many researches on this subject [47, 48, 49, 50].

When the above data are considered, BEP-tr consists of three parts which are

a) Meeting the building heating and cooling net energy requirement,

b) Determination of lighting loads and

c) Calculation of energy consumption with the mechanical systems which will fulfill the building net energy requirement [46].

The method used is "Simple Hourly Dynamic Calculation Methodology". The basis of choosing this method is impracticability of detailed dynamic methods, not essentially requiring to determine the heating and cooling seasons as it is in monthly/seasonal static methods and being able to calculate the net energy amount in changeover seasons [51].

Simple hourly dynamic calculation methodology;

a) is a half dynamic calculation method. Hourly climate data and time schedules are used,

b) Resistance - Capacity (RC) model can reflect hourly thermal behavior of the building in a more real-like way,

c) It allows for comfort conditions to be identified depending on the operative temperature,

d) It calculates the operative temperatures with hourly calculation steps and required net energy which will provide for the comfort requirements according to hourly time schedule [52].

Calculation methodology of Energy Performance of Building in Turkey which is a national calculation method has been prepared for our country and is based on existing measurements and evaluations which are used in terms of geographical, architectural and construction techniques. It aims to calculate net energy amounts of buildings, determine their energy classes and create certain awareness in issues such as harms to the environment and CO_2 emission amounts. Thanks to the application in new buildings to be built as of July 2011 and imposing an obligation to give Energy

Identity Certificate (EIC) to the buildings, it is among the most important expectations that it will play an important role in terms of exhausting energy sources and accelerating the solution processes for them [46].

2.2.4 TUBITAK project

After the developments in the way of increasing building energy efficiency in EU and Turkey, the research project was improved which is entitled “Determination of Turkish Reference Buildings and National Method for Defining Cost Optimum Energy Efficiency Level of Buildings” by a research team in Istanbul Technical University (ITU). The project, numbered as 113M596, was supported by Scientific and Technological Research Council of Turkey (TUBITAK) and conducted between 2013 and 2015 [53].

This research project bases on Directive 2010/31/EU the methodology framework that took place in “Annex III” of the Directive. The purpose is developing a legislation compatible framework for national cost optimal energy efficiency level calculations in Turkey.

Determination of reference building is the first stage of this methodology framework so the residential buildings were identified in selected pilot region according to building stock firstly. The pilot region was selected as Istanbul because this city includes the building typology and occupancy profile at most in Turkey. The climate type of Istanbul is warm and humid.

Firstly, the buildings were categorized collecting general data about residential building types for determining building typologies. These typologies were categorized as Single Family Houses, Standard Apartments (below 2000 m^2), Standard apartments (above 2000 m^2), Residences (Luxury High-Rise Residential Buildings). According to Article 12 Building Energy Performance Regulation published in Resmi Gazette in 01/04/2010,in the new buildings; central heating system is used if the total usage area which is the basis of the building license is 2.000 m^2 and above [54]. However, this article of the Regulation includes only new buildings starting from 2009. Therefore, Standard Apartments were divided into two typologies as below 2000 m^2 and above 2000 m^2 for after 2009 in this project. Before 2009, there aren’t any distinctions for Standard Apartments.

Afterwards, the building physical properties (geometry, orientation, transparency ratios, shading elements, number of floors…), building thermo-physical properties (heat transfer coefficients, solar heat gain coefficients, visible light transmittances, thermal bridges,…), lighting system properties (powers, luminance levels,…), HVAC system properties (fuel types, efficiencies, powers, flow rates,…), DHW system properties (flow rates, powers,…), occupancy densities, heat gains, schedules were provided from different resources. The building information such as number of floors, structural system, construction materials, heating system, DHW system, and fuel type was obtained from Turkish Statistical Institute (TUIK). However, some of this information in TUIK was given for certain years for example the heating systems, DHW systems, and fuel types were only existent between 2002 and 2012. Therefore, the missing information was obtained via national and international standards (ASHRAE, EN, TS 825 and Green Building Certification Guide), existing building projects and meetings with experts. Furthermore, the heat transfer coefficients were obtained from TS 825 in this research project and TS 825 has been updated in accordance with the years. Thus, all building typologies were indicated according to construction years divided in between construction years of 1985-1999, 2000-2008 and 2009-2012. At the end of this data collection, 26 reference buildings for three different time period between 1985 and 2012 were identified.

After the identification of reference buildings, the cost-optimal methodology framework in accordance with Directive 2010/31/EU was adapted. Firstly, these reference buildings were modeled using detailed dynamic building simulation tools (DesignBuilder and EnergyPlus) in order to analyze the annual energy consumptions and energy performances. Secondly, the energy efficient measures that include passive and mechanical system retrofits were integrated to these reference building models as single measures and improvement packages. Then, these models were simulated to test if the energy efficient measures were increased the energy performances of these buildings. Thirdly, the global cost calculations based on net present value methodology of reference buildings and their energy performance improvements retrofits were carried out during their economic lifecycle. Besides, the sensitivity analyses also were performed for the data used in global cost calculations. Finally, the cost-optimum energy efficiency levels of these retrofits were defined and the framework of the national method was created in coherence with national circumstances.

According to the project results, the energy efficiency measures (standard retrofits) enhanced the energy performance of single family house and apartment block retrofits reducing their annual energy consumptions effectively. However, these standard measures became less effective on luxury high-rise residential building retrofits comparing with other residential building typologies due to the difference of their transparency ratios, heat gains, and especially complexity of HVAC system properties. Moreover, the luxury high-rise residential buildings are the most complicated residential building typology which has thermal interactions between other occupied areas such as offices, shopping malls, fitness and social facilities included in their complex structure. Besides, the mechanical ventilation systems are used generally in these residential typologies because these are tall buildings and it is not possible to use operable windows after a certain height to ventilate the dwellings naturally owing to low pressure and high wind effects. Therefore, the annual heating, cooling and ventilation consumption of these buildings are higher than the other residential typologies and HVAC systems are needed which are more efficient, use the renewable energy systems and able to use the heat recovery of lost thermal energies of buildings in the vicinity to meet high energy consumption of these buildings efficiently.

2.2.5 Republic of Turkey national renewable energy action plan, 2014

This action plan depends on the Directive 2009/28/EC of The European Parliament and of The Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC sets.

The main reason of this plan is the increasing of energy consumption in Turkey remarkably compared to other countries. Primary energy consumption was 129.7 MTEP in 2015 and increased by 46% from 2005 to 2015. Turkey, 75.9% of primary energy demand in 2015 were met from foreign sources of energy, therefore Turkey is among the countries with high dependence on foreign energy. At the below, the primary energy consumption of Turkey depending on time is illustrated in Figure 2.4.

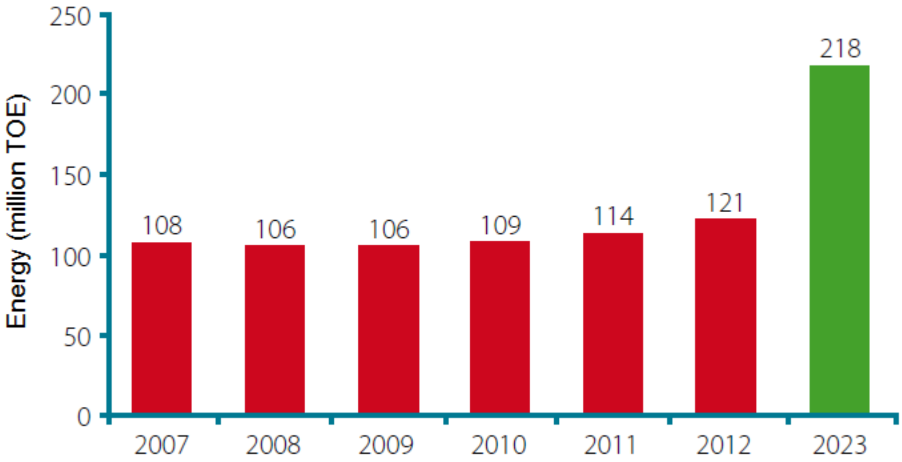

Figure 2.4 : The primary energy consumption of Turkey (the consumption of 2023 is an estimated value) [55].

The ranges of different renewable energy sources in terms of million Tons of Oil Equivalent (TOE) in Turkey are shown in Figure 2.5. In 2012, the total amount of energy generation based on renewable energy sources was 12.1 million so this amount of energy generation is 10% of total primary energy consumption of Turkey. Therefore, it was considered that the electricity generation from renewable energy sources and promotion of energy efficiency measures were the two priorities of Turkeys' energy policy in order to reduce of energy resource dependency of Turkey.

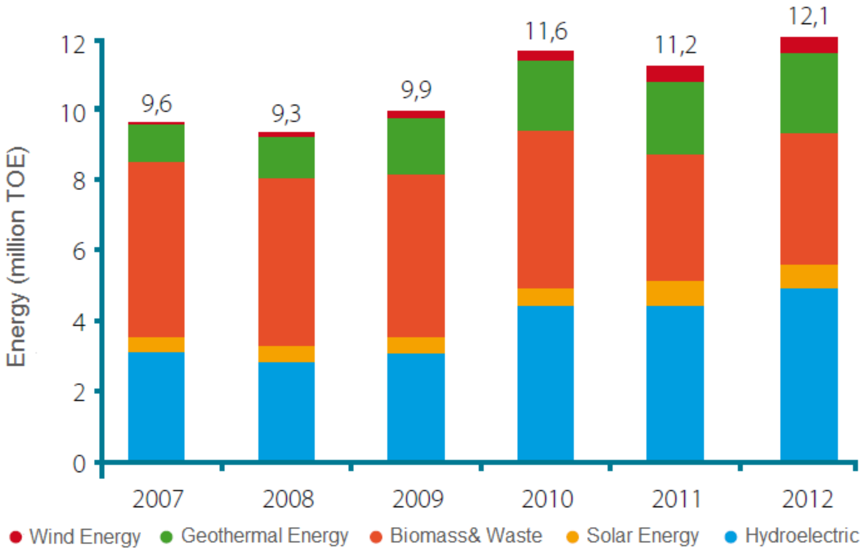

Figure 2.5 : The renewable energy generation of Turkey [55].

With this action plan depended on Directive 2009/28/E, it was targeted to increase the energy generation by utilizing renewable energy sources in Turkey by 20% minimum until 2023. In Figure 2.6, the installed capacity of renewable energy sources and the electricity generation from renewable energy sources is demonstrated for 2013 and the target of 2023 in Turkey.

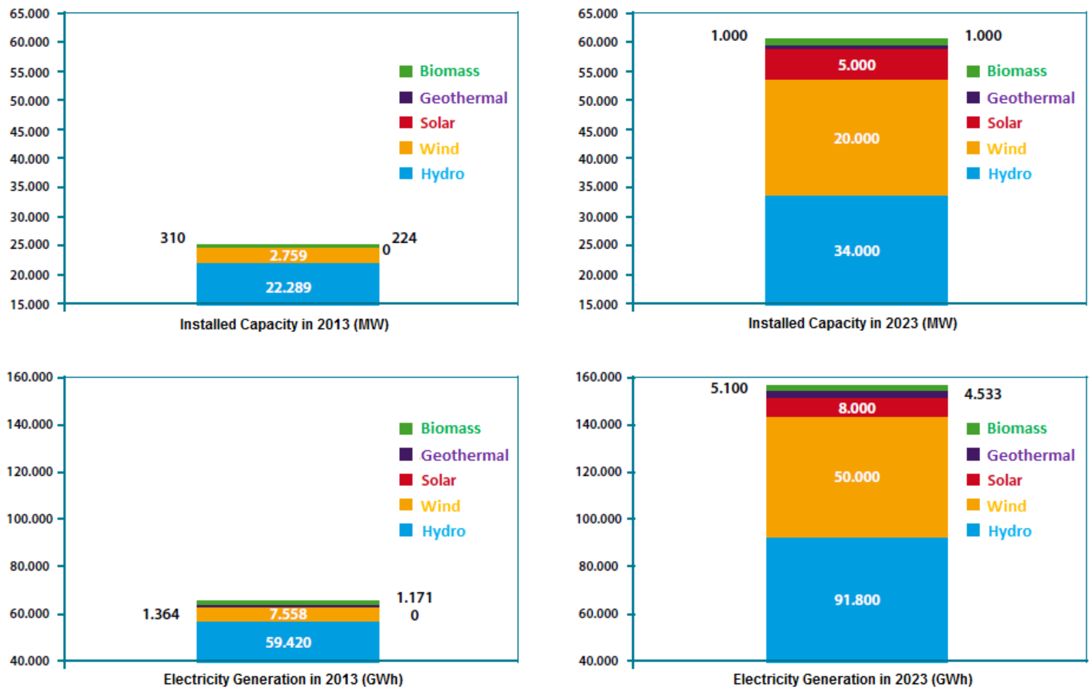

Figure 2.6 : The installed capacity of renewable energy sources and the electricity generation from renewable energy sources for 2013 and the target of 2023 [55].

2.2.6 Republic of Turkey national energy efficiency action plan, 2017

The main purpose of this national plan is the reduction of Turkeys' total primary energy consumption to 23.9 million TOE between 2017 and 2023 by utilizing energy end natural resources efficiently and environmentally-responsible so ensure the highest contribution to national development.

This plan bases on mainly supplementing Directive 2012/27/EU. This plan includes 55 action plans related to energy savings in buildings and services, energy, transport, industry, technology and agriculture. The action plans for horizontal buildings in the national action plan are as following:

a) Action 1: Establishing energy management systems and increasing efficiency,

b) Action 2: Development of national energy efficiency financing mechanism,

c) Action 3: Supporting energy efficiency projects with energy efficiency competitions,

d) Action 4: Creating guides, engagement and etc… including technical, legal and financial matters in energy efficiency projects,

e) Action 5: Development of registration, database and reporting systems in energy efficiency activities,

f) Action 6: Improving, coordinating and controlling opportunities and efficiencies of international energy efficiency financing,

g) Action 7: Strengthening the administrative and institutional settlement,

h) Action 8: Performing of awareness, educating and consciousness raising,

i) Action 9: Energy efficiency studies,

j) Action 10: Adoption of sustainable enterprise and purchasing approach in public sector,

k) Action 11: Energy efficiency liability program for energy distribution or retail companies.

3. THE ENVIRONMENTAL AND ECONOMIC IMPACTS OF THE HIGH-RISE BUILDINGS

Looking at the worldwide, human population continues to grow rapidly and the demand for buildings as shelters increases, which in turn leads societies to choose high-rise buildings as a solution. However, these kinds of buildings are not environment and cost friendly because tons of concrete and steel are consumed and many heavy machineries and equipment are operated during their construction process. In addition to, these buildings' mechanical systems such as HVAC, building automation system (BAS), elevator and escalator systems are high costs that consume too much fossil fuel. Therefore, in order to achieve more energy efficient high-rise buildings a new balance needs to be applied between these two factors, which are also motivated by both environmental and economic concerns.

3.1 Environmental Concerns

High-rise buildings are often related with high resource consumption needing building materials in large amounts during construction, significant amounts of energy for building operations and also result in huge waste amounts upon getting demolished by the end of their life cycle. Being highly reliant on building systems (i.e. HVAC and vertical transportation systems), above 75% of energy consumption in high-rise buildings is given out to HVAC [56, 57]. Further, tall buildings exert an adverse effect on the microclimate due to wind funneling and turbulence around their bases, causing discomfort to pedestrians. They cast a shadow on nearby buildings, streets, parks, and open spaces, and they may obstruct views, reduce access to natural light, and prevent natural ventilation [58]. Therefore, we will need to increase the energy efficiency of high-rise buildings to decrease the damage of their environmental impact.

3.1.1 Energy and carbon emission

The high-rises' construction and operation require great energy and generate significant amounts of carbon emission and air pollution that contribute to global warming. High-rises consume lots of steel and cement-manufacturing these materials requires lots of energy and generates large amounts of carbon dioxide. Also, tall buildings' construction requires great energy and generates considerable carbon dioxide because of operating heavy machinery and equipment such as powerful cranes and pumps (e.g., pumping water and concrete to upper floors) and dump trucks. Transporting building materials from far distances (sometimes across the globe) also consumes energy and produces immense carbon dioxide [56, 57].

Alternative eco-friendly materials (e.g., local wood, earth, clay, or gravel that have smaller ecological footprint than steel and concrete) are not suitable for constructing these buildings. However, recently, architects and structural engineers have been experimenting with using compressed wood for constructing tall buildings. Further, these buildings consume great energy and generate significant greenhouse emission resulting from running mega electrical, mechanical, lighting, and security systems. Architects have built skyscrapers with poor thermal performance and without natural ventilation, meaning that buildings' owners need to continuously heat and cool indoor spaces (in the winter and summer respectively) to make sure that tenants have comfortable indoor environments. As such, the energy needed to heat and cool these skyscrapers is not only costly but also hurts the environment by generating massive carbon dioxide [58, 59, 60].

3.1.2 Urban heat island effect

The urban heat island (UHI) effect refers to an increase in temperature in dense inner city locations over the fringe of the same city. The concentration of heat in urban areas or UHI could increase temperature by 10 - 12 Fahrenheit degrees, according to Rudi Scheuermann [61]. The temperature increase is a result of the massive concentration of urban areas-made up of heat-retaining materials, such as asphalt, concrete, steel, bricks, and impervious ground and roof surfaces, which collectively act as a huge thermal mass that absorbs solar radiation during the day and discharges it in the form of long-wave heat radiation during the night. Overall, when extreme heat occurs, high-rise cities have more trouble cooling off than other places do, creating a greater demand for energy to cool spaces. Also, heat waves aggravate both indoor and outdoor thermal discomfort and negatively affect people's health when the human body cannot cool off at night [62].

3.1.3 Wind

Urbanization weakens natural ventilation because buildings block breezes coming from nearby natural fields such as ocean, sea, lakes, forests, farms, and mountains [61]. Given their greater heights and larger masses, tall buildings impact natural wind directions and patterns by increasing the distance of wind shadow and minimizing the air flow in the leeward direction, i.e., behind buildings. Therefore, in polluted urban environments, decreased airflow augments stagnation and accumulation of air pollution [62].

At the street level, tall buildings create a wind tunnel effect that increases wind speed and turbulence, which discomforts pedestrians. Strong airflow that occurs around tall buildings creates eddies, loops of dust and air pollution, thereby disturbing and discomforting street activities. Wind acceleration manifests in open areas, including plazas, passages, entrances, corners, and spaces between buildings [63].

Additionally, it is well known that natural ventilation as one of the energy efficiency improvement measures is powerful tool to reduce buildings energy demand, but its efficiency is very dependent on the wind – outdoor air velocities. If wind velocity is too small natural ventilation is not sufficient and mechanical ventilation is to be turned on. Foster Norman's tower office building Comerzbank Frankfurt (completed in 1997) is famous as an energy efficiency landmark, known also as a prototype for an ecological high-rise building. It receives natural daylight and ventilation which can be natural and mechanical – it means mixed. Very innovative for high-rise building, the Comerzbank's mixed ventilation solution did operate with certain problems because its control (turning mechanical ventilation on and off) was not appropriately controlled [64]. By the conducted research [64], problem of mixed ventilation control has been solved analytically and verified by measurements [65].

3.2 Economic Concerns

High-rise buildings are costly buildings. Their costs are greater than that of low-rise buildings holding the same square footage because they need stronger foundation and structural systems to withstand natural forces of wind, gravity, and earthquakes, and to resist severe weather conditions such as hurricanes, tornados, and typhoons [66]. These buildings also require expensive vertical transportation such as elevators and escalators, as well as enormous energy to pump water to upper floors. On the other hand, the occupants living in high-rise residential buildings have more annual income compared to others living in single family houses and apartment buildings. For this reason, their annual energy requirements are higher in order to ensure high thermal comfort during the year. Although HVAC systems that condition these buildings are high efficient, the initial investment costs of these systems are very expensive and annual energy costs are also high because they works all the time through the year.

3.2.1 Costs of HVAC systems

The heating, cooling, ventilation, humidification and dehumidification are carried out by HVAC systems with high capacity in high-rise buildings during the year in order to provide better indoor environmental quality. Moreover, these systems are controlled by BAS generally to control the HVAC systems depending on occupant density, thermal load and weather conditions. The initial investment costs of HVAC systems in these building are higher because the more powerful pumps and longest piping systems are needed to transport the conditioned water from basement floor to top floor of the building. On the other hand, HVAC systems are selected as high efficient and their capacities are over the peak energy demand of the building to ensure high thermal conform during the year. Additionally, the mechanical ventilation systems are needed to ensure required fresh air for the occupants in high-rise buildings because the natural ventilation is not possible due to their rise and high wind effect depending on high rise. Besides, the maintenance and operation costs of these costly systems are also expensive. When all these costs are considered together, the mechanical system investment cost of high-rise residential buildings become higher compared to other residential building types. Moreover, all these systems consume large amounts of energy depending on fossil resources so the energy costs of these building become higher because all HVAC systems are operated continuously to ensure better indoor air quality during the year.

3.2.2 Inadequate use or lack of renewable energy systems

Because of the fossil fuel limitations, we have to develop a new mechanism to substitute these sources of energies with renewable energies, which are dramatically based on environment and climate. Thus, although, assessing 100% renewable energy sources is extremely complicated task, by implementing them as a source of power, buildings could be ‘environment friendly’ and attain ‘zero emission’ [67]. Unfortunately, the prices of the parcels in which high-rise buildings are located are quite high so the installation and application of renewable energy systems such as solar collectors and PV systems are not possible. If it was possible, the high-rise buildings surrounding the city would decrease the efficiency of these systems due to shading effect. When considered the heat pump systems, the capacity of these systems would be very high and the suitable weather conditions, land areas or water basins with high thermal mass are required in order to apply these systems. For the use of wind energy, the desired conditions must be ensured such as topography, vegetation, urban settlement, wind direction, wind speed etc.

4. A NEW APPROACH FOR THE ENERGY AND COST OPTIMIZATION OF HVAC SYSTEMS SUPPORTED BY ALTERNATIVE AND RENEWABLE ENERGY TECHNOLOGIES IN LUXURY HIGH-RISE RESIDENTIAL BUILDINGS IN A BUILDINGS' COMPLEX

This new approach was improved based on cost-optimal methodology framework in Directive 2010/31/EU which includes the reducing of the primary energy consumptions of buildings taking into account global costs of these buildings in their expected economic lifecycles. Besides, this new approach was become a unique and appropriate for Turkeys' conditions by adapting the developments related with increasing of building energy performance in EU. It has been seen that a similar approach hasn't been defined yet when the necessary literature investigation was done. It is intended to be a guide for the applications for decreasing the primary energy consumption of luxury high-rise residential buildings in Turkey by using this new approach.

4.1 Purpose of the Approach

The main scope of this thesis study is reducing the annual primary energy consumption of HVAC systems by utilizing the renewable energy systems, the high efficient HVAC systems and the heat recovery of lost thermal energies of buildings in the vicinity in luxury high-rise residential building typology taking in to account global costs of these systems during the expected economic lifecycle of the building.

According to literature review, there isn't any approach related with reducing the annual primary energy consumption of luxury high-rise residential building HVAC systems by applying advanced retrofit measures through adapting the methodology framework in Directive 2010/31/EU to Turkey's conditions. The construction of luxury high-rise residential building types has been rising increasingly in Turkey as a result of the demand of luxury conditions in houses amoung high income groups and the HVAC systems of these buildings consume high energy based on fossil fuels generally. Thus, the more detailed research is needed for improving the energy performance of this residential building typology in Turkey.

In this thesis study, it is aimed not only to reduce the primary energy consumption of the luxury high-rise residential buildings to the optimum level but also to use the energy resources of the country at optimum level. The other aim of this thesis is to reduce the energy dependency of Turkey with technological HVAC systems that use renewable energy resources and the heat recovery of lost thermal energies of buildings existed in the vicinity.

This thesis methodology adapted Turkeys' conditions using this new approach can be applied to both new and existing buildings. In addition, since this residential building typology has similarities with commercial buildings in terms of having different usage areas in their own structure, it is aimed that this methodology will be a guideline for determining the cost optimum energy efficiency levels of commercial buildings to be built in the future.

4.2 Steps of the Approach

Since the methodology of this approach bases on Directive 2010/31/EU, the methodology steps of this approach were improved fallowing this directive. These steps are fallowing:

- Determination of the case study buildings that represents the luxury high-rise residential buildings,
- Calculation of primary energy consumption of case study buildings
- Determination of retrofit measures applied to case study buildings,
- Calculation of primary energy consumption of renovated buildings,
- Calculation of global costs
- Making relevant sensitivity analyzes for the financial data used in the analyzes,
- Identification of cost-optimum energy efficiency level for luxury high-rise residential building.

4.2.1 Determination of the case study buildings that represents the luxury high-rise residential building typology in the selected pilot region

The designation of the reference building for this residential building typology is very important because this designation refers to the building data ensures minimum requirements of construction, lighting system, electrical appliances, operating schedules, occupant density, HVAC and DHW system properties in accordance with the country conditions. In addition, the comparison of the energy performance between retrofits and reference building shows whether the retrofits are implemented successfully in terms of reducing the annual primary energy consumption.

There are three different methods to define reference buildings; real building method, example building method, virtual building method [23]. In this thesis study, the reference building was defined by real building method so the selected case study building that represents the luxury high-rise residential buildings exist in pilot region was considered as a reference building. The energy performance variations of all renovated buildings were analyzed by applying retrofit measures to this case study building.

The envelope thermo-physical and optical properties, boundary conditions data, thermostat values, occupant densities, heat gains, lighting systems, operational schedules, ventilation rates, HVAC and DHW systems properties of case study building was ensured by technical team of energy management department in this building. In the methodology of this approach, the passive system properties (envelope thermo-physical and optical properties, boundary conditions data, thermostat values, occupant densities, heat gains, lighting systems, operational schedules) were not changed when the energy performance of retrofits are improved. The energy improvements were carried out in order to increase the performance of HVAC and DHW system of case study building. However, the climatic conditions, geometry, thermostat values, occupant densities and heat gains should be same for each building that includes also reference building in order to compare the energy performances of these buildings accurately. Therefore, these building parameters were not also changed in any renovated buildings in this research.

In this thesis study, there are different case study buildings in terms of the amount of fresh air supplied by air handling units.

4.2.2 Calculation of primary energy consumption of case study buildings as a reference case

The annual primary energy consumption of each case study building is calculated using the detailed dynamic methodology by using simulation tools according to EN 13790 Standard. According to this standard, annual primary energy consumption of these buildings can also be calculated by measurement method but this method is not possible to perform owing to lack of representative real building in building stock and it could be misleading for Turkeys' condition also. For this reason, the annual primary energy consumption of case study buildings with using their building data ensured by technical team of energy management department in the building is calculated using DesignBuilder and EnergyPlus simulation tools which use detailed dynamic calculation methodology.

EnergyPlus is DOE's open-source whole-building energy modeling (BEM) engine, the successor to DOE-2.1E. Under development since 1997, EnergyPlus embodies the state-of-the-art in BEM knowledge in a comprehensive and robust engine that is continuously maintained, thoroughly documented and fully supported. EnergyPlus implements detailed building physics for air, moisture, and heat transfer including treating radiative and convective heat-transfer separately to support modeling of radiant systems and calculation of thermal comfort metrics; calculates lighting, shading, and visual comfort metrics; supports flexible component-level configuration of HVAC, plant, and refrigeration systems; includes a large set of HVAC and plant component models; simulates sub-hourly time steps to handle fast system dynamics and control strategies; and has a programmable external interface for modeling control sequences and interfacing with other analyses. EnergyPlus is tested according to ASHRAE Standard 140 methodology, which is currently being extended with measured data from well-characterized, highly instrumented test facilities [68].

DesignBuilder is a user-friendly modelling environment where you can work with virtual building models. It provides a range of environmental performance data such as: energy consumption, carbon emissions, comfort conditions, daylight illuminance, maximum summertime temperatures and HVAC component sizes. DesignBuilder uses the EnergyPlus dynamic simulation engine to generate performance data [69].

In this thesis study, the geometric modeling of the buildings was carried out by using DesignBuilder due to lack of user-friendly interface of EnergyPlus. Since DesignBuilder uses the EnergyPlus dynamic simulation engine, geometric data could easily be transferred to EnergPlus. Then, the collected building data for the case study buildings was entered by using EnergyPlus and the building model is completed and ready for simulation. The climatic data of pilot region was taken into account by using Typical Meteorological Year (TMY) data of Istanbul to analyze the annual primary energy consumption and thermal behavior of the building under climatic conditions. This data includes all climatic parameters (outdoor dry bulb temperature, wet bulb temperature, relative humidity, wind speed, direct radiation, diffuse radiation...) throughout the simulation period (8760 hours).

For the calculation of annual primary energy consumption of the building, the each consumption result based on fuel type should be multiplied to the energy conversion factor determined by Turkish Ministry of Environment and Urbanization. In this research, these factors are ensured by Green Building Certification Guide. If these factors are updated by Ministry or related institutions, the current energy conversion factors should be used. According to the guide, the conversion factor is 2.36 for electricity and 1 for natural gas for Turkey. The primary energy consumption calculation as follows,

Where:

- PEC_e is primary energy consumption for electricity,
- T_e is conversion factor for electricity.
- PEC_n is primary energy consumption for natural gas,
- T_n is conversion factor for natural gas,
- PEC_t is total primary energy consumption.

$$PEC_e = T_e \times 2.36 \tag{4.1}$$

$$PEC_n = T_n \times 1 \tag{4.2}$$

$$PEC_t = PEC_e + PEC_e \tag{4.3}$$

4.2.3 Determination of retrofits measures applied to case study buildings

As mentioned before, more detailed research is needed for the luxury high-rise residential buildings in TUBITAK project in order to further reduce annual primary energy consumption. The energy efficient retrofits should be developed for HVAC system that are more efficient, benefit from renewable energy sources and use the heat recovery of lost thermal energies of buildings in the vicinity. Thus, these retrofit measures that are more energy efficient and consume less fossil sources should be applied to case study buildings and the energy performance of each measure should be tested by using detailed dynamic simulation tools. These retrofit measures have been determined by taking into account the current case study buildings. In other words, the measures were determined to reduce the annual primary energy consumption of each case study buildings improving HVAC system properties. For this reason, the energy efficient retrofits were developed changing existing HVAC system properties or applying technological HVAC systems to case study buildings.

In this part, these measures are divided into standard and advanced retrofit measures as follows:

4.2.3.1 Standard retrofit measures

Standard retrofit measures include the energy improvements of HVAC systems by increasing efficiencies of system components, controlling of system flow rates depends on load and occupancy density and replacing of existing systems with more efficient systems.

4.2.3.2 Advanced retrofit measures

Advanced retrofit measures contain the energy improvements of HVAC systems by upgrading existing HVAC systems with more technological HVAC systems, ensuring the energy needs of existing HVAC systems from renewable energy sources or the heat recovery of lost thermal energies of buildings in the vicinity.

The standard and advanced measures consist of single measures or packages that include combination of single measures. In addition, one part of packages are improved by combining only standard or advanced retrofit measures while other part of packages are improved by using standard and advanced measures together.

4.2.4 Calculation of primary energy consumption of renovated buildings

The energy performance tests of retrofit measures were carried out by using DesignBuilder and EnergyPlus simulation tools as well as case study buildings' energy performance test. After the energy performance simulations, the each consumption result based on fuel type is multiplied to the energy conversion factor published as mentioned previous parts. Then, all primary energy consumptions should be summed in order to obtain total primary energy consumption annually.

4.2.5 Calculation of global costs

The scope of this approach is to determine cost-optimum energy efficiency level by improving retrofit measures for HVAC system of case study building. However, these measures are not be considered accurately without global cost calculations of these systems. In order to determine of each building global cost during expected economic lifecycle, it is necessary to calculate the initial investment costs, running costs, replacement costs and residual values of HVAC systems as follow.

4.2.5.1 Calculation of initial investment cost

Initial investment costs, C_I, to be considered when the building (or the specified equipment) is delivered to the customer, ready to use. These costs include design, purchase of systems and components, connection to suppliers, installation and commissioning process. The initial investment costs are the costs presented to the customer. The initial investment cost is directly related to the market conditions. The sanitary engineering companies, HVAC system manufacturers, suppliers and exporters and necessary government bodies (Ministry of Energy, Ministry of Environment and Urbanization…) should be in communication with each other. In addition, the current mechanical and electrical projects are needed to calculate accurate initial investment costs of HVAC systems.

In this thesis research, initial investment costs of HVAC systems were calculated using the publication of Construction and Installation Unit Prices of Ministry of Environment and Urbanization. For the HVAC unit prices not included in this publication, tenders were received from the project companies on the market.

TAXs were added into all gathered costs. Initial investment costs are calculated using equation 2.4.

4.2.5.2 Calculation of annual cost

Annual cost, C_a, is sum of running costs and periodic costs or replacement costs paid in the year.

4.2.5.3 Calculation of running cost

Running cost, C_r, comprise maintenance costs, operational costs, energy costs and added costs.

4.2.5.4 Calculation of maintenance cost

Maintenance cost, C_m, is annual costs for measures for preserving and restoring the desired quality of the installation. This includes annual costs for inspection, cleaning, adjustments, repair under preventive maintenance, consumable items.

4.2.5.5 Calculation of operational cost

Operational costs, C_o, are annual costs for operators.

4.2.5.6 Calculation of energy costs

Energy costs, C_e, are annual costs for energy and standing charges for energy (and other consumables as well as costs). In order to calculate energy costs for Turkey, natural gas unit price is taken 0.109775 TL/kWh, electricity unit price is taken 0.366371 TL/kWh considering 2015 values including TAX [70, 71]. The annual costs of HVAC system energy consumptions would be defined by multiplying these unit prices with the related energy consumption of each fuel types. The increase in energy costs was assumed as equal to the inflation rate in this research.

4.2.5.7 Calculation of replacement costs

Replacement costs comprise periodic costs for component or system. In order to define replacement costs, the lifespan data of HVAC systems is needed and this data could be ensured from HVAC system manufacturers and suppliers or EN 15459 Standard, Annex A, Table A.1.

4.2.5.8 Economic assumptions for global cost calculation

The assumptions on economic indicators as follow,

- The inflation rate, R_i, is annual depreciation of the currency expressed in R_i % is taken as 8.05%, according to the statistics of Turkish Republic Central Bank's last 5 years' average value [72].

- The market interest rate, R, agreed by lender expressed in %. The average of the last 5 years was selected as the market interest rate to be used in the main calculations. Therefore, the market interest rate is 14.3% [73].

- The discount rate, R_d, (present value factor) is definite value for comparison of the value of money at different times. The discount rate calculated using equation 2.5 is equal to 5.78%.

4.2.6 Making relevant sensitivity analyzes for the financial data used in the analyzes

According to Directive 2010/31/EU, cost calculations and projections with many assumptions and uncertainties, including for example energy price developments over time, are generally accompanied by a sensitivity analysis to evaluate the robustness of the key input parameters. For the purpose of the cost-optimal calculations, the sensitivity analysis should at least address the energy price developments and the discount rate; ideally the sensitivity analysis should also comprise future technology price developments as input for the review of the calculations [74].

The purpose of sensitivity analysis is to identify the most important parameters of a cost optimal calculation. Member States shall perform a sensitivity analysis on the discount rates using at least two discount rates each expressed in real terms for the macroeconomic calculation and two rates for the financial calculation. One of the discount rates to be used for the sensitivity analysis for the macroeconomic calculation shall be 3% expressed in real terms. Member States shall perform a sensitivity analysis on the energy price development scenarios for all energy carriers used to a significant extent in buildings in their national context. It is recommended to extend the sensitivity analysis also to other crucial input data [74].

Results of the sensitivity analyses on economic indicators should be assessed by investigating the new cost-optimal levels with an increased energy performance which may be obtained through variations. The retrofit scenarios which may be regarded as in cost-optimal range but still require further support should also be considered in the evaluation of the results [75].

4.2.7 Identification of cost-optimum energy efficiency level

After calculating annual primary energy consumption and global cost for reference building, case study building and renovated buildings, the comparison of primary energy consumption and global cost results is used simultaneously in order to identify the cost-optimum energy efficiency level. Therefore, in order to provide this comparison, a graph should be drawn while yearly primary energy consumption (kWh/m².a) locating on X axis, global cost (currency/m²) locates on Y axis. The case/cases that provide cost-optimum energy efficiency level can be determined by monitoring the changes in global cost and primary energy consumption for the retrofit measures through this graphical plot.

In case if the measures are not cost-optimum then the most energy efficient measures should be taken into account if possible [76].

5. APPLICATION OF THE SUGGESTED NEW APPROACH TO DIFFERENT CASE STUDY BUILDINGS TO DECREASE PRIMARY ENERGY CONSUMPTION AND GLOBAL COST

5.1 Determination of the First Case Study Building

In this study, the existing building was selected from the residential blocks of the Kanyon building located in Levent, Istanbul and all studies on determining the cost-optimum energy efficiency level were carried out for A Block of these residences. Kanyon Project is built as one of the largest mixed-use buildings in Europe that includes residential buildings, offices and shopping mall in Turkey by İş GYO and Eczacıbaşı Group. Kanyon consists of a shopping mall with 4 floors, an office block with 26 floors and a residential block with 179 residences [77]. The general view of A Block selected as a case study building in this research and Kanyon mixed-use building is demonstrated in Figure 5.1.

Figure 5.1 : The general view of Kanyon mixed-use building and A Block.

5.1.1 Definition of architectural system parameters

A Block has 16 floors and consists of 42 residences. There are completely residences between 1st and 15th floors of the building and a machinery room on the 16th floor. There are social facilities, shopping mall and parking area before the first floor of the building. In this study, non-residential areas up to the first floor of the building were not included in the energy model of the building and the surface between residential and non-residential area was assumed to be an adiabatic surface. Thus, there is no heat transfer between these areas according to this assumption. The net area and the number of rooms in each residence in the building are designed differently depending on the floors. As seen in Table 5.1, the net areas and number of rooms for residences block is shown.

Table 5.1 : The net areas and number of rooms of residences in A Block.

	Residence Types	Number of Rooms	Area (m^2)
Between 1st and 7th residence floors	D1 D2	1 + 1	108.06
	D3 D4	1 + 1	116.48
2nd residence floor North side	D1B2	3 + 1	229.05
Between 8th and 13th residence floors	D1B D2B	4 + 1	220.9
14th residence floor South side	D2C	4 + 1 (duplex)	329.9
14th residence floor North side	D1B3	1 + 1	191.3
15th residence floor North side	D1B4	2 + 1	191.4

The locations of residence types are illustrated in the architectural plan view in Figure 5.2. For the building energy model, the thermal zone areas for each residence in the floors are also shown in this figure. As seen from the figure, each residence is assumed a thermal zone.

Figure 5.2 : The thermal zone areas on architectural plan of A Block.

The building components were determined based on the material layers proposed by the architectural project group. The overall heat transfer coefficients (U-values) of opaque and transparent components of the building façade are shown in Table 5.2.

Table 5.2 : The overall heat transfer coefficients (U-values) of opaque and transparent components.

Building Component	U – value (W/m²K)
External Wall	0.298
Roof	0.645
Windows	1.65

Thermo-physical and optical properties of transparent façade component was collected from the building energy management. The obtained data is shown in Table 5.3.

Table 5.3 : Thermo-physical and optical properties of the glazing and the frame.

Building Element	U – value (W/m²K)	SHGC	T-vis
Glazing	1.56	0.447	0.551
Frame	1.8	-	-

Briefly, the number of the occupants for each apartment unit was determined in accordance with the room numbers since this is an existing case condition. Additionally, since the occupant profiles of these buildings are high-income group a stayed-in or a daily housekeeper was defined for each apartment unit. In summary there are two, three and four-person families in this case study building. So, there are 3 different operation schedules for occupancy. The operational scenario for occupancy was defined according to the published researches by Ministry of Family and Social Policies in 2011 and 2013 [78, 79]. Activity levels of the occupants were specified in accordance with ASHRAE 55 – Thermal Environmental Conditions for Human Occupancy standard [80]. User intensity diverse from 33 to 38 m²/person. Only in three of the apartment unit types, this value is different; in D1B3 type 63 m²/person, in D2C type 54 m²/person and in D1B4 47 m²/person [77].

Operation schedule for 2-person family with a daytime housekeeper (housekeeper during weekdays between 08:00-17:00) is shown in Table 5.4; for 3-person family with a daytime housekeeper in Table 5.5; for 3-person family with a stay-in housekeeper in Table 5.6; and for 4-person family with a stay-in housekeeper in Table 5.7 [77].

Table 5.4 : Occupancy operation schedule for 2-person family with a daytime housekeeper.

	Hours	Number of People	Activity
Weekdays	00:00-07:00	2	Sleeping
	07:00-08:00	2	Getting ready
	08:00-17:00	1	Housework
	17:00-23:00	2	Dinner, House activities
	23:00-24:00	2	Sleeping
Saturday	00:00-11:00	2	Sleeping, Reclining
	11:00-12:00	2	Breakfast, Getting ready
	12:00-18:00	0	-
	18:00-20:00	2	House activities
	20:00-23:00	0	-
	23:00-24:00	2	Sleeping, Reclining
Sunday	00:00-11:00	2	Sleeping, Reclining
	11:00-12:00	2	Breakfast, Getting ready
	12:00-15:00	0	-
	15:00-23:00	2	Dinner, House activities
	23:00-24:00	2	Sleeping, Reclining

Table 5.5 : Occupancy operation schedule for 3-person family with a daytime housekeeper.

	Hours	Number of People	Activity
Weekdays	00:00-07:00	3	Sleeping
	07:00-08:00	2	Getting ready
	08:00-17:00	1	Housework
	17:00-18:00	2	House activities
	18:00-23:00	3	Dinner, House activities
	23:00-24:00	3	Sleeping
Saturday	00:00-11:00	3	Sleeping, Reclining, Standing
	11:00-12:00	3	Breakfast, Getting ready
	12:00-18:00	1	House activities
	18:00-20:00	3	House activities
	20:00-23:00	2	Dinner, House activities
	23:00-24:00	3	Sleeping, Reclining
Sunday	00:00-11:00	3	Sleeping, Reclining, Standing
	11:00-12:00	3	Breakfast, Getting ready
	12:00-15:00	1	House activities
	15:00-23:00	3	Dinner, House activities
	23:00-24:00	3	Sleeping, Reclining

Table 5.6 : Occupancy operation schedule for 3-person family with a stay-in housekeeper.

	Hours	Number of People	Activity
Weekdays	00:00-07:00	4	Sleeping
	07:00-08:00	2	Getting ready
	08:00-17:00	1	Housework
	17:00-18:00	2	House activities
	18:00-23:00	4	Dinner, House activities
	23:00-24:00	4	Sleeping
Saturday	00:00-11:00	4	Sleeping, Reclining, Standing
	11:00-12:00	4	Breakfast, Getting ready
	12:00-18:00	2	Housework
	18:00-20:00	4	House activities
	20:00-23:00	3	Dinner, House activities
	23:00-24:00	4	Sleeping, Reclining

Table 5.6 (continued) : Occupancy operation schedule for 3-person family with a stay-in housekeeper.

	Hours	Number of People	Activity
Sunday	00:00-11:00	4	Sleeping, Reclining, Standing
	11:00-12:00	4	Breakfast, Getting ready
	12:00-15:00	2	Housework, House activities
	15:00-23:00	4	Dinner, House activities
	23:00-24:00	4	Sleeping, Reclining

Table 5.7 : Occupancy operation schedule for 4-person family with a stay-in housekeeper.

	Hours	Number of People	Activity
Weekdays	00:00-07:00	5	Sleeping
	07:00-08:00	2	Getting ready
	08:00-17:00	1	Housework
	17:00-18:00	2	House activities
	18:00-23:00	5	Dinner, House activities
	23:00-24:00	5	Sleeping
Saturday	00:00-11:00	5	Sleeping, Reclining, Standing
	11:00-12:00	5	Breakfast, Getting ready
	12:00-18:00	3	Housework, House activities
	18:00-20:00	4	House activities
	20:00-23:00	2	Dinner, House activities
	23:00-24:00	5	Sleeping, Reclining
Sunday	00:00-11:00	5	Sleeping, Reclining, Standing
	11:00-12:00	5	Breakfast, Getting ready
	12:00-15:00	2	Housework, House activities
	15:00-23:00	5	Dinner, House activities
	23:00-24:00	5	Sleeping, Reclining

In Table 5.8, the average electric power and operating times of household electrical appliances used in each residence are domonstrated.

Table 5.8 : Electrical household appliances and operating times.

Household Electrical Appliances	Power (W)	Operating Time
Refrigerator	54.3	All day (24 h)
Oven	3100	6 hours / week
Electrical Stove	7200	Weekdays: 2 hours / day Saturday: 2 hours / day Sunday: 1.5 hours / day
Range Hood	290	Weekdays: 2 hours / day Saturday: 2 hours / day Sunday: 1.5 hours / day
Dishwasher	1399	4 hours / week
Washing Machine	718.2	4 hours / week
Tea Maker	1650	All week: 2 hours / day
Iron	2600	6 hours / week
Vacuum Cleaner	1450	4.5 hours / week
TV	128	Weekdays: 3 hours / day Weekends: 5 hours / day
Laptop	88	Weekdays: 3 hours / day Weekends: 5 hours / day

The electrical power data used in the calculations is provided by the producer of electrical household appliances [81, 82, 83].

The lighting power and lighting power densities that are illustrated in Table 5.9 were provided by electricity project group of Kanyon Residence.

Table 5.9 : Lighting power densities of each residence.

Residence Units	Lighting Power (W)	Lighting Power Density (W/m²)
Between 1st and 7th residence floors	D1, D2: 1100	10.18
	D3, D4: 1100	9.44
2nd residence floor North side	D1B2: 2657	11.6
Between 8th and 13th residence floors	D1B, D2B: 1850	8.4
14th residence floor South side (duplex)	D2C: 7250	21.97
14th residence floor North side	D1B3: 1900	9.9
15th residence floor North side	D1B4: 1850	9.7

5.1.2 Definition of HVAC system parameters

The mechanical conditioning systems of case study building are defined at below.

5.1.2.1 Heating system parameters

There are two condensing boilers to heat the residential blocks of Kanyon. These heaters are fueled by natural gas and the heating capacity is 970 kW for each boiler. Each boiler has 93% efficiency considering the lower heating value (LHV) of natural gas and these systems operate between 70°C and 40°C. These boilers heat the residences through radiators depending on the heating demands of the residences.

5.1.2.2 Cooling system parameters

There are two chillers for cooling the residential blocks of Kanyon. These systems are water-cooled screw chillers and the capacity of each system is 784.1 kW. These systems supply cooling water to the fan coil systems in residences to meet the cooling demand of the building. These cooling systems operate between 7 and 12°C and the efficiency of each system becomes 5.63 COP when the systems work in full capacity. The energy performance of these chillers cooling the residential block under partial loads is shown in Table 5.10.

Two closed circuit cooling towers with each capacity of 900 kW are used whenever chiller operates. Operating temperature of these cooling towers is between 30°C and 35°C

Table 5.10 : The system capacities, electrical powers and efficiencies of the chillers under partial loads.

Load (%)	Capacity (kW)	Electrical Power (kW)	Efficiency (COP)
100	784.1	139.2	5.63
75	588.1	89.3	6.58
50	392.0	49.1	7.98
25	196	33.9	5.78

5.1.2.3 Ventilation System Parameters

The ventilation of residences is ensured by two air handling units (AHU) which are fully fresh air. These systems supply fresh air to saloons and bedrooms according to mechanical project. There are no heat recovery systems and economizer in these systems. Moreover, there are no extract fans in these systems and the type of supply fans is constant air volume. In WC, showers, kitchens and utility rooms, exhaust fans exist according to mechanical project. In building energy model, all ventilation systems condition entire zones. The ventilation systems properties are demonstrated in Table 5.11.

Table 5.11 : The ventilation system properties.

Air Handling Units	Air Flow Rate [m^3/s]	Rated Fan Power [W]	Fan Efficiency [%]
AHU A1	4.07	6,600	0.79
AHU A2	3.5	6,600	0.78

The minimum ventilation rates in breathing zone obtained from ASHRAE 62.1 Standard are demonstrated in Table 5.12 at below.

Table 5.12 : The minimum ventilation rates in breathing zone.

Occupancy Category	People Outdoor Air Rate (R_p) [L/s.person]	Area Outdoor Air Rate (R_a) [$L/s.m^2$]
Dwelling	0.125	0.245

Operating temperature for heating coils in air handling units is between 40°C and 60°C. Supply air temperature is between 20°C and 22°C in heating seasons. In cooling seasons, supply air temperature is 19°C for dehumidification. In Table 5.13, the fresh and exhaust air flow rates for each zone are illustrated.

For domestic hot water system, two hot water storage tanks are used and each capacity is 2000 lt. Operating temperature is 50°C for heating seasons and 40°C for cooling seasons. Average monthly domestic hot water consumption is 300 m^3 for all dwellings. Besides, pumping system type is variable.

Table 5.13 : The total fresh air and exhaust air flow rate of each zone.

	Fresh Air Flow Rate [m^3/s]	Exhaust Air Flow Rate [m^3/s]
Between 1st and 7th residence floors	0.125	0.245
2nd residence floor North side	0.235	0.320
Between 8th and 13th residence floors	0.235	0.320
14th residence floor South side (duplex)	0.425	0.350
14th residence floor North side	0.235	0.320
15th residence floor North side	0.235	0.320

In addition, all the HVAC system in the building are monitored by using a building automation system and this system controls if the HVAC systems work required at operating temperatures, flow rates, etc. Besides, this building automation system informs the faults coming out in HVAC systems.

5.2 Determination of the Second Case Study Building

This building is similar to first case study building in terms of the location, climate zone, building typology and the interaction with the buildings in the vicinity. All the architectural system parameters of second case study building are also similar to first case study building such as the floor and room number, architectural plans, the volume and areas of thermal zones, heat transfer coefficients (U-values) of opaque and transparent components, construction layers, operating schedules, lighting powers, heat gains and set-point temperatures. Besides, the heating and cooling system parameters are similar to first case study building except the mechanical ventilation system. In second case study building, the amount of fresh was reduced by half of first case study building by considering TS 825. Accordingly, the electrical powers of each blower fan in AHUs were also decreased due to reduced fresh air flow rates because there is no need to use high-capacity fans for fresh air flow rate that has been reduced in half. Therefore, there will be more energy saving on annual electricity consumption by using low capacity fans. Other than this, all technical properties of mechanical ventilation system of his building is similar to first case study building. The ventilation systems properties are illustrated in table at below.

Table 5.14 : The ventilation system properties of second case study building.

Air Handling Units	Air Flow Rate [m^3/s]	Rated Fan Power [W]	Fan Efficiency [%]
AHU A1	2.60	4,000	0.79
AHU A2	2.60	4,000	0.78

Besides, the fresh and exhaust air flow rates for each zone are illustrated in Table 5.15 at below.

Table 5.15 : The total fresh air flow rate of each zone in second case study building.

	Fresh Air Flow Rate [m³/s]
Between 1st and 7th residence floors	0.08
2nd residence floor North side	0.176
Between 8th and 13th residence floors	0.169
14th residence floor South side (duplex)	0.386
14th residence floor North side	0.169
15th residence floor North side	0.216

5.3 Calculation of Primary Energy Consumption of First Case Study Building

The energy model of first case study building was modeled in detailed-dynamic building simulation tools (DesignBuilder and EnergyPlus) by using the building parameters of the building. Figure 5.3 shows the model view of A Block modeled by using DesignBuilder.

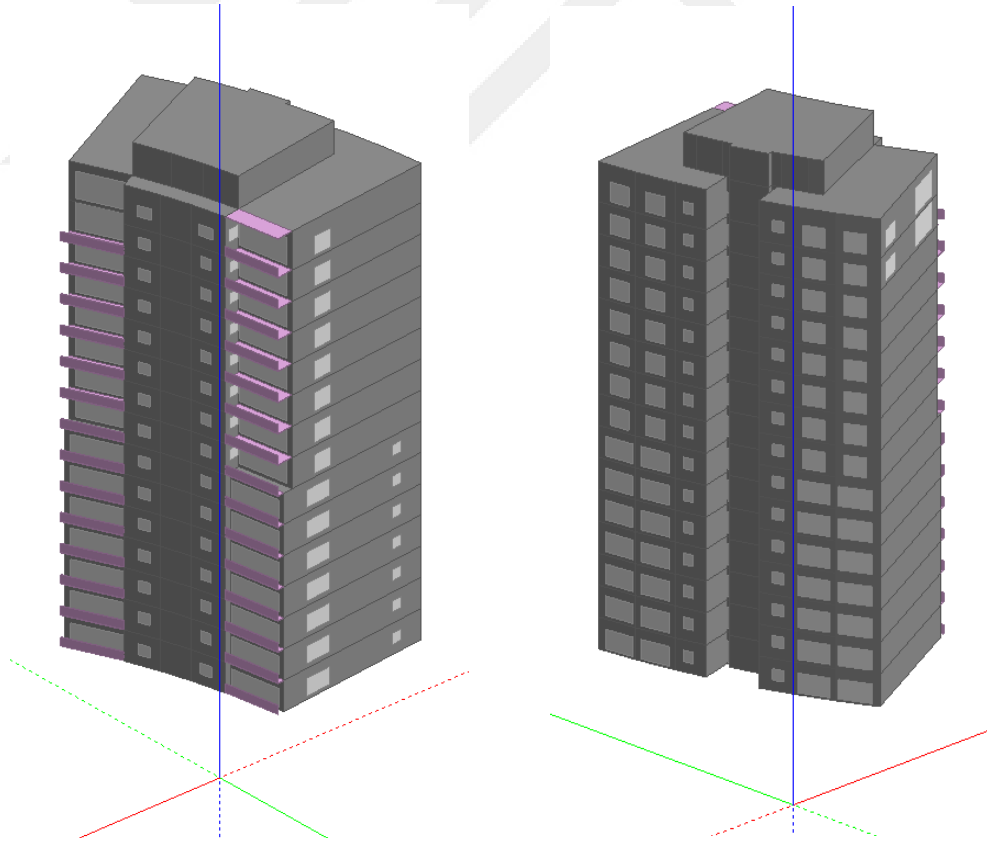

Figure 5.3 : The model view of South-west and North-east facade of A Block respectively.

Then, the architectural systems of the building and then the HVAC systems are modeled so the building energy model was completed. Finally, the annual energy consumption of case study building was simulated by using annual climatic data of Istanbul. Then, the energy consumption of each fuel type consumed by the building was converted to primary energy and the annual total primary energy consumption was obtained by using Equation 4.1, 4.2 and 4.3.

The total area of the building model is 6,575.41 m^2. The annual energy consumption and the annual primary energy consumption of case study building calculated by using EnergyPlus are illustrated in Table 5.16. In this table the annual energy consumption of case study building is expressed in terms of consumption subgroups.

Table 5.16 : The annual energy consumptions and the annual primary energy consumptions of first case study building.

Consumption Subgroups	Electricity [kWh/m^2.a]	Natural Gas [kWh/m^2.a]	Electricity [PE/m^2.a]	Natural Gas [PE/m^2.a]
Heating	0.0028	107.05	0.0066	107.05
Cooling	9.97	0	23.53	0
Interior Lighting	19.12	0	45.11	0
Interior Equipment	59.40	0	140.184	0
Fans	26.35	0	62.19	0
Pumps	1.6385	0	3.867	0
TOTAL	116.48	107.05	274.90	107.05

As seen from the results, the heating energy consumption of the building is quite high. This is why, this case study building is a residential building and the residential building types have lower annual heat gain due to low occupant density and low usage of interior lighting and equipment when they are compared to the other building types. In addition, the construction system components used to design the facade system of this building were selected to meet the heating demand of the building because this case study building is a residential building so the general aim of façade design is reducing the heat losses during the building's heating period. The correctness of this purpose is seen easily while looking at the Table 5.16. Looking at the heating consumption in terms of primary energy of the buildings, it is higher than the cooling consumption. The condensing boilers used to heat the residences are high efficient system considering LHV at 93% efficiency. Besides, the water cooled screw chiller is also high efficient systems used to cool the residences. These systems achieve a COP of 5.63 in case of full capacity and continue to operate maintaining high efficiency in partial loads. The heating and cooling systems of the building are designed as systems that meet the heat losses and heat gains efficiently but the climatic conditions are also taken into account by mechanical project team in order to design these systems. The building is located in Istanbul and Istanbul is in the warm - humid climate zone. In this climate zone, there are no extreme temperatures during heating and cooling seasons and there are no large temperature differences between day and night because of the humid climate. This climatic region is warm during the year but the heating period is longer than the cooling period also the apparent temperature is higher than the dry-bulb temperature due to humidity. Therefore, the heating and cooling systems of the building are designed by considering the user density, heat gains construction systems and climatic region. Looking at to annual primary energy consumption of fans, it is understood that these systems are the second consumption group that consume highest energy in the building after heating. The fresh air requirement of luxury high-rise residential buildings is generally met by mechanical ventilation instead of natural ventilation that is why the energy consumption cost of mechanical ventilation systems is also involved to the annual costs unlike the other types of residential buildings.

5.4 Calculation of Primary Energy Consumption of Second Case Study Building

The second case study building was also modeled by using similar building simulation tools and the energy performance was tested annually under the same climatic conditions. Both annual energy consumption and annual primary energy consumption results of second case study building expressed in terms of consumption subgroups was illustrated in Table 5.17.

Table 5.17 : The annual energy consumptions and the annual primary energy consumptions of second case study building.

Consumption Subgroups	Electricity [kWh/m^2.a]	Natural Gas [kWh/m^2.a]	Electricity [PE/m^2.a]	Natural Gas [PE/m^2.a]
Heating	0.0023	88.72	0.0054	88.72
Cooling	9.21	0	21.74	0
Interior Lighting	19.12	0	45.11	0
Interior Equipment	59.40	0	140.184	0
Fans	20.40	0	48.14	0
Pumps	1.64	0	3.87	0
TOTAL	109.78	88.72	259.08	88.72

At the below, the comparison of first and second case study building in terms of primary energy consumption is demonstrated in Figure 5.4. As seen from the figure, the annual heating energy consumption of second case study is less than the first case study building. The reason of this result is the less natural gas consumption of heating coils in AHUs due to the reduction of fresh airflow rate by half in the building.

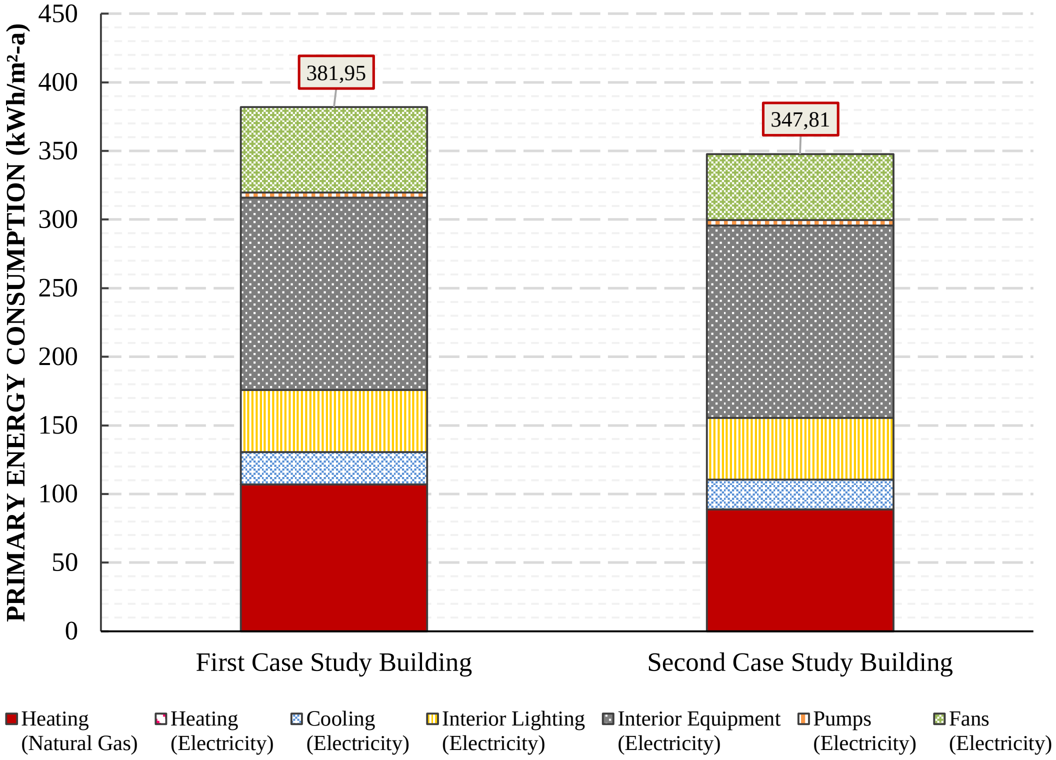

Figure 5.4 : The comparison of annual primary energy consumption between first and second case study building.

The difference of annual natural gas consumption between first and second case study building is 18.33 kWh/m^2.a. Looking at the figure, the other remarkable energy reduction is fan consumption by 14.05 kWh/m^2.a. The main reason of this reduction is the decline of the electrical power of fans so the less electricity is consumed by the blower fans of AHUs annually. Other hand, it is seen that, the annual cooling energy consumption difference is 0.76 kWh/m^2.a approximately when Table 5.16 and Table 5.17 is compared. The reason of this little energy consumption difference is that the case study building is a residential building in which the cooling energy demand is less than the heating energy demand. Besides this case study building is located in a warm - humid climate zone that the cooling season is shorter than heating season and there are no high temperatures in cooling season compared to warm - dry climate zones at the south of Turkey.

5.5 Determination of Retrofits Measures Applied to Case Study Buildings

In the following, standard and advanced retrofit measures applied to the mechanical systems of building are introduced to increase the energy efficiency of the building.

5.5.1 Standard retrofit measures

The standart retrofit measures are defined in detail at below.

5.5.1.1 The effect of heat recovery units on building energy performance

An air handling units of existing building are constant air flow system with 100% fresh air. In these systems, there is no heat recovery unit. The heat recovery unit is a heat exchanger integrated in air handling unit that ensures to heat or cool the fresh air by utilizing heat energy of return air, thereby less energy is consumed when the fresh air is conditioned by used these systems. Therefore, the heat recovery units integrated in air handling units of case study buildings were tested whether they contribute to the building's energy efficiency. In Figure 5.5, the operation of heat recovery unit is demonstrated in a heating season. In this study, two heat recovery units in different efficiency were tested as two different scenarios.

- In the first scenario, a heat recovery unit with 75% sensible heat effectiveness was tested.
- In the second scenario, a heat recovery unit with both 75% sensible and 50% latent heat effectiveness was tested.

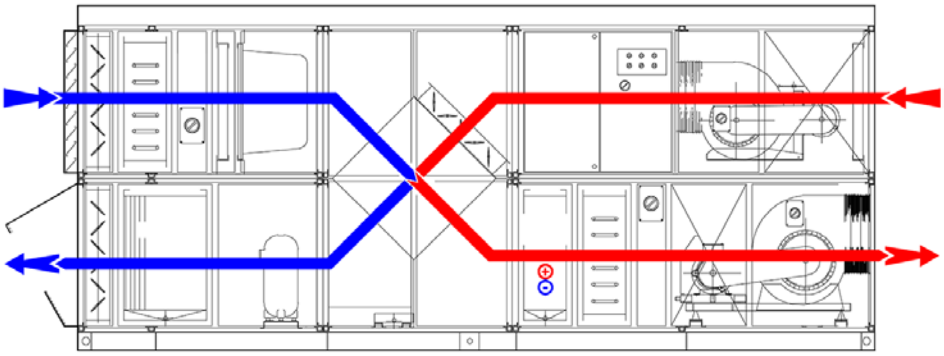

Figure 5.5 : The image of heat recovery unit in the air handling unit operating in a heating season.

5.5.1.2 The effect of economizer on building energy performance

The air handling unit is able to cool the indoor environment supplying air by fans without operating cooling coils if the outdoor air is at certain temperature and humidity range especially in transition seasons. This cooling process by using economizer is known free cooling. In this process, the building saves electricity because cooling coils does not operate through the cooling process of building. Therefore, the usage of economizer in air handling units of case study buildings was tested if it contributes to the building's energy efficiency. Three different type of economizer were tested in this study as three different scenarios.

- In the first scenario, the effect of economizer with FixedDryBulb on existing building energy performance was tested. FixedDryBulb means the economizer will set the outdoor airflow rate at minimum if the outdoor air temperature is higher than a specified dry-bulb temperature limit.
- In the second scenario, the effect of economizer with DifferentialDryBulb on existing building energy performance was tested. DifferentialDryBulb will trigger the outdoor airflow to minimum when the dry-bulb temperature of outdoor air is higher than the dry-bulb temperature of the return air.
- In the third scenario, the effect of economizer with FixedEnthalpy on existing building energy performance was tested. FixedEnthalpy checks the upper limit of the enthalpy given as a field input against the enthalpy content of outdoor air and will set the outdoor airflow rate to minimum if the latter is greater than the former.

5.5.1.3 The effect of radiant heating system on building energy performance

Nowadays, it is known that, it is possible to save higher energy using radiant heating system than the radiator and fan coil systems. With this system, the indoor environment is heated by natural convection heat transfer via rising of heated air by using lower boiler operating temperature without compromising the comfort conditions. Therefore, the impact of radiant heating system on building energy performance was tested when the current system (radiator) of the case study buildings was changed with this system. In this energy improvement scenario, the boiler operating temperature range was reduced to 50/30°C from 70/50°C. Furthermore, the system was controlled so that the floor temperature did not exceed

28°C so it is ensured that the user comfort is not affected by the increase in surface temperature. The application of radiant heating system is shown in Figure 5.6.

Figure 5.6 : The image of radiant heating system application.

5.5.1.4 The effect of chilled ceiling system on building energy performance

With using chilled ceiling system, the cooled air descends from ceiling to floor by natural convection heat transfer and chills the indoor environment. This system is used to chill rather than cool the building that’s why the cooling performance of this system is lower than the performance of fan coils and air conditioners. On the other hand, this system saves higher energy due to operating in higher chilled water temperature than the other cooling systems. The application of chilled ceiling system is shown in Figure 5.7.

Figure 5.7 : The image of chilled ceiling system application.

During the chilling process, the condensation may generate on the surface of pipes of this system in the case of using lower chilled water temperature. Therefore, the higher chilled water temperature is used to prevent the condensation. In this energy improvement scenario, the chiller operating temperature range was increased to 7/12°C from 10/15°C.

5.5.1.5 The effect of ground source heat pump on building energy performance

In this study, the ground source heat pump which utilizes the ground thermal energy was tested while this system was using instead of the boilers and chillers that are the main conditioning system in case study buildings. The energy loop of ground source heat pump is illustrated simply in Figure 5.8 at below.

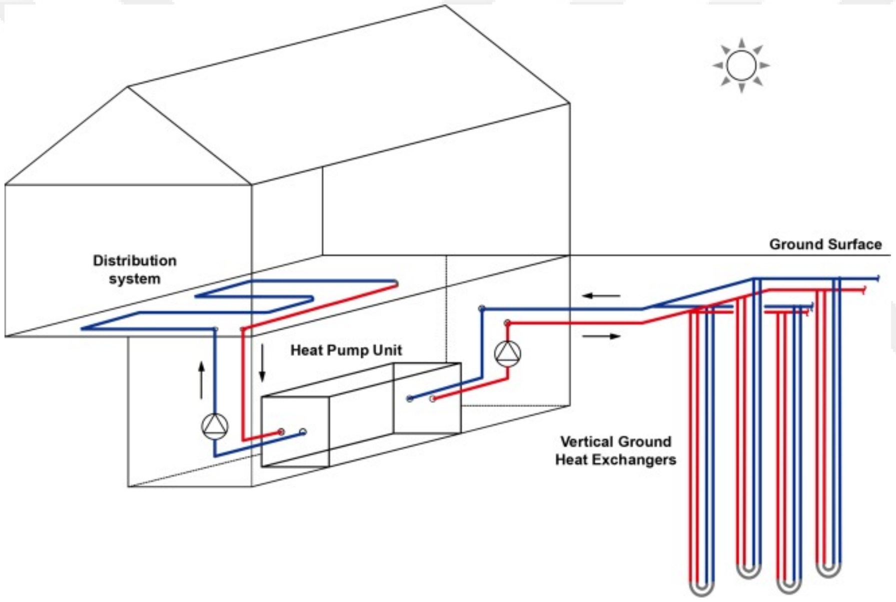

Figure 5.8 : The image of thermal energy loop of ground source heat pump.

Two different type scenarios were tested in this study for the first and second case study building.

- For the first case study building, the ground source heating pumps’ heating capacity is 778 kW and cooling capacity is 350 kW. In addition, 120 boreholes are needed and the each borehole length should be 76 m in order to extract the required thermal energy stored in the earth for conditioning the first case study building.
- For the second case study building, the ground source heating pumps’ heating and cooling capacity does not change. However, the amount of boreholes is reduced by half and 60 boreholes are sufficient to condition the second case

study building. Besides, the each borehole length is kept as 76 m in order to extract the required thermal energy stored in the earth.

5.5.1.6 The effect of heat recovery ventilator on building energy performance

The air handling units used in case study building are fully fresh air and constant air flow systems. Instead of this system, the heat recovery ventilator was used for each residence unit. This system consists of three main components: air to air heat exchanger, blower fan and exhaust fan as seen in Figure 5.9.

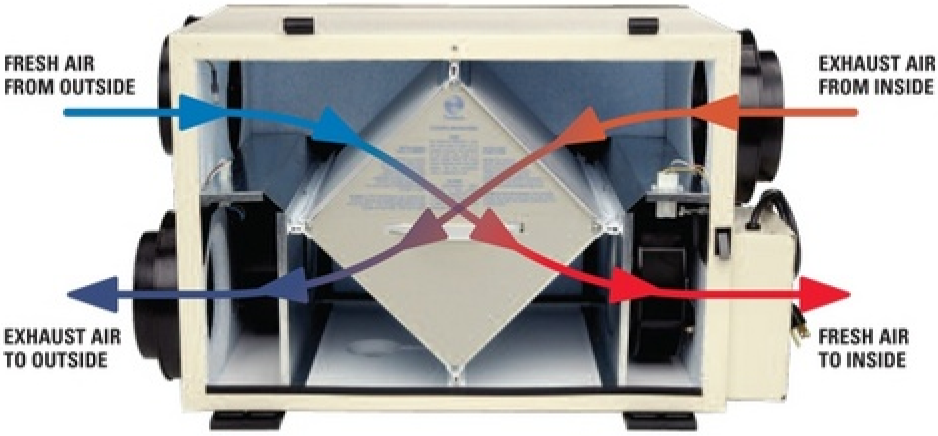

Figure 5.9 : The image of heat recovery ventilator.

In this system, the thermal energy of the exhaust air is used to condition the fresh air then the conditioned air is delivered to the residence units. Thus, the required fresh air is conditioned without using a heating or a cooling coil. In this retrofit measure, the fan flow rate in each heat recovery ventilator equals to fresh air requirement of each residence unit.

5.5.1.7 The effect of mechanical ventilation system dependent on occupant density on building energy performance

The existing air handling units in the building blows a constant amount of fresh air hourly to the residence units. Instead of blowing of fresh air to each residence unit hourly, in this retrofit measure the effect of air handling units working dependent on occupant densities, on building energy performance was tested.

5.5.2 Advanced retrofit measures

The advanced retrofit measures are defined in detail from the beginning of next page.

5.5.2.1 The effect of combined heat and power (CHP) systems on building energy performance

In this retrofit measure, the combined heat and power systems (cogeneration and trigeneration systems) were used to improve the energy performance of the case study buildings.

In the first scenario, a cogeneration system was used in order to ensure thermal energy for heating the building instead of the existing condensing boiler. This system is used to heat the residence units, produce sanitary hot water and generating electricity.

- For the first case study building, both thermal power and electrical power is 500 kW of this cogeneration system.
- For the second case study building, the capacity of cogeneration system was declined due to the reduction of conditioned fresh air flow rate ensured by air handling units. Therefore, both thermal power and electrical power is 400 kW of system in second case study building.

In the second scenario, a trigeneration system was used to supply thermal energy for heating and cooling the building. This system is used to heat the residence units, produce sanitary hot water, generate electricity. It also cool the building by utilizing the exhaust gas thermal energy of this system. The trigeneration systems are used with the cooling system called the absorption chiller that converts thermal energy of the exhaust gas to cooling energy by using lithium bromide-water ($LiBr\text{-}H_2O$) or ammonia-water ($NH_3\text{-}H_2O$) solution. As a result, the residence units are cooled by chilled water produced by an absorption chiller that converts exhaust gas thermal energy to cooling energy.

- For the first case study building, both thermal power and electrical power is 500 kW of this trigeneration system and the cooling capacity of absorption chiller is 250 kW in this scenario.
- For the second case study building, both thermal power and electrical power is 400 kW of trigenerationsystem in second case study building. However, the cooling capacity of absorption chiller was kept constant as 250 kW because the cooling demand of second case study building does not reduce as more as heating demand owing to be residential building type.

EnergyPlus and EnergyPro simulation tools were used together to achieve the building energy performance test results in this study. EnergyPro is the modeling software for combined techno-economic optimization and analysis of a variety of heat, CHP, process and cooling related energy projects. With EnergyPro it is possible to easily model, optimize, simulate and analyze all kinds of energy plants in existing systems or greenfield energy projects. The software optimizes the operation of the modeled system in accordance to all preconditions such as weather conditions, technical properties of the different units, maintenance costs, fuel prices, taxes, subsidies, etc [84]. In the below, the model view of CHP systems in building energy loop ensured from EnergyPro are shown in Figure 5.10 and Figure 5.11.

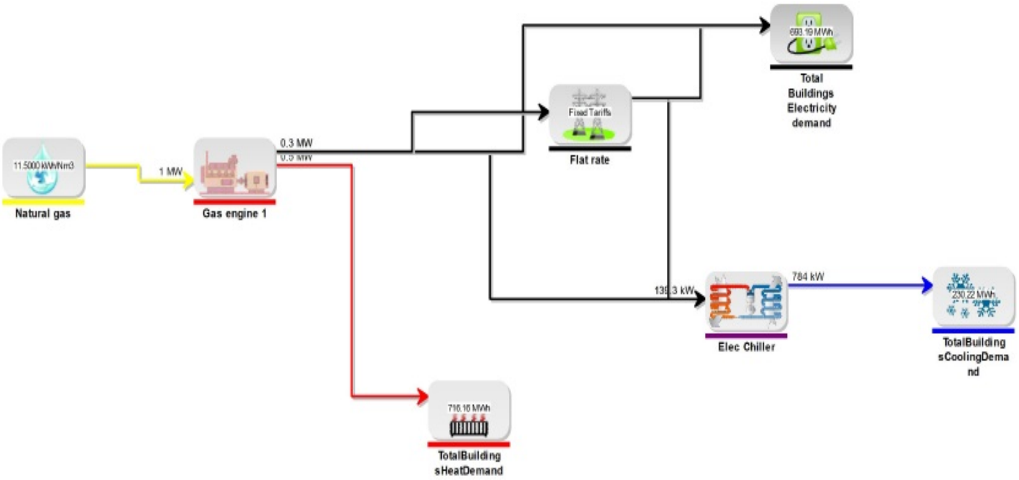

Figure 5.10 : The view of cogeneration system layout.

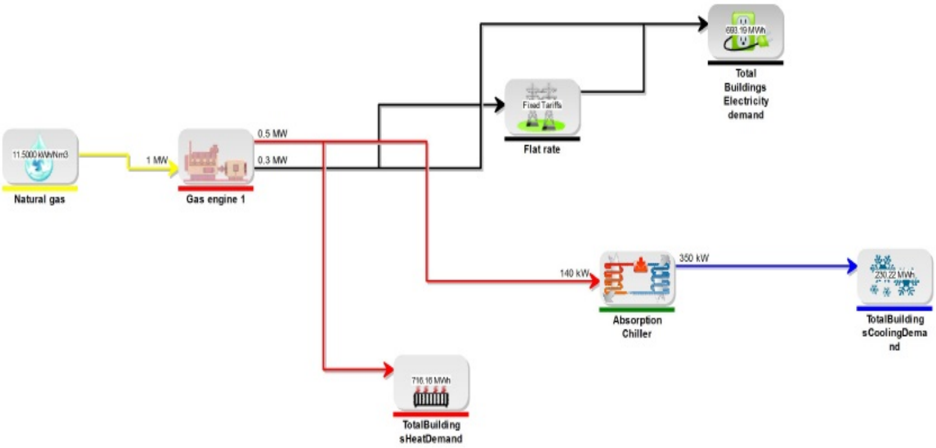

Figure 5.11 : The view of trigeneration system layout.

5.5.2.2 The effect of hybrid ventilation on building energy performance

The building energy performance was tested when natural ventilation was done and the mechanical ventilation system was stopped simultaneously by a building automation system controlled by indoor and outdoor enthalpy sensors. In this scenario, the mechanical ventilation systems are stopped by BAS when the windows are opened automatically by using window actuator systems as seen in Figure 5.12 controlled by the same BAS at the certain enthalpy of indoor and outdoor environment. There were two different scenarios was tested for the first and second case study building:

- When the windows are opened it is assumed that 2 ach of fresh air entered to each residence unit in the first case study building because it is seen that the air handling units blow fresh air to each residence unit approximately 2 ach fresh air when look at to Table 5.13.
- For the second case study building, it is assumed that 1 ach of fresh air entered to each residence unit when the windows are opened because the amount of fresh air was reduced by half in this building compared to first case study building.

Figure 5.12 : The view of window actuator system.

5.5.2.3 The effect of solar assisted sanitary hot water production system on building energy performance

Today, it is known that the solar collectors which are used in the production of sanitary hot water with high energy efficiency ensure to increase building energy performance with a correct mechanical design. Therefore, the impact of 45 flat plate solar collectors on case study buildings energy performance which are placed with certain intervals on existing building roof was tested. Each solar collector that has an area 2.5 m^2 operates to support hot water tank by ensuring hot water and this tank is continued to support by existing condensing boiler by the reason of the seasons in which less solar radiation. In Table 5.18, the technical properties of solar collector used in case study building are shown.

Table 5.18 : The technical data of solar collector.

	Unit	Dimension
Total surface area	m^2	2.51
Absorber surface area	m^2	2.32
Optical efficiency	%	75.4
Heat loss coefficient U1	W/(m^2.K)	4.15
Heat loss coefficient U2	W/(m^2.K^2)	0.0114
Thermal capacity	kJ(m^2.K)	4.5
Fluid capacity	USG	0.44
Maximum working pressure	bar	6
Maximum stagnation temperature	°C	196

In Figure 5.13, the dimensions of solar collector that are ensured from technical documentation of manufacturer using for generating hot water is demonstrated.

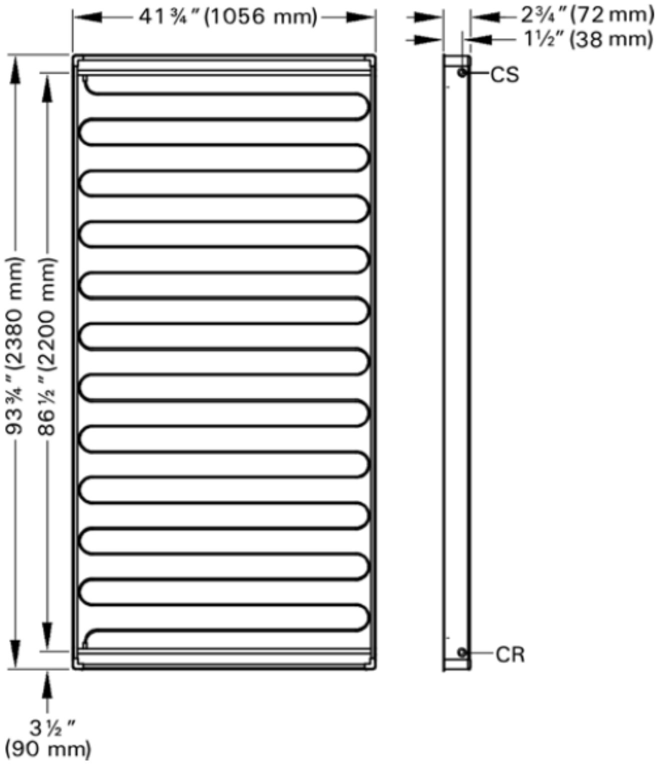

Figure 5.13 : The dimensions of solar collector (all units provided are imperial, SI units provided in parentheses).

The solar energy system that operates supported by central heating system when the amount of solar radiation is less to produce domestic hot water is seen in Figure 5.14. According to this, the hot water produced by solar collectors are transferred to a hot water tank by a pump in order to aid to increase the temperature of tank water. In hot water tank, there are two copper serpantines that one is linled to solar collector system and the other is linked to central heating system. Therefore, the less natural gas is consumed by using solar energy system especially in cooling seasons to heat the cold running water to required temperature.

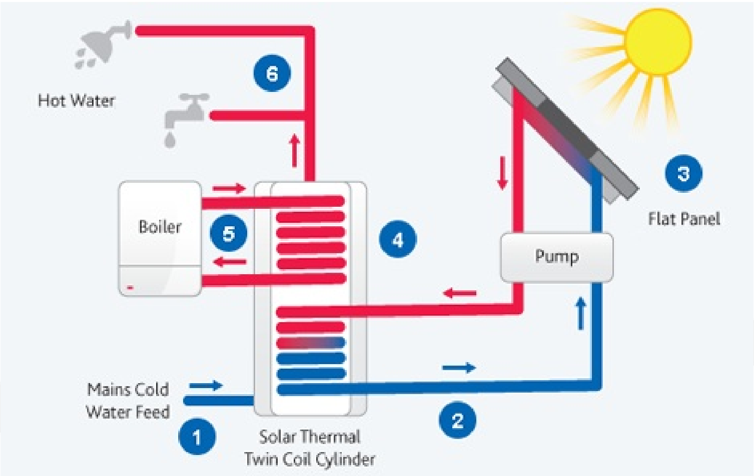

Figure 5.14 : The energy loop of solar assisted sanitary hot water production system.

5.5.2.4 The effect of solar assisted building heating system on building energy performance

In this retrofit measure, the solar collector system which is used to support the existing heating systems by producing hot water are utilized to tested whether the energy efficiency of case study building increases. The energy loop of solar assisted system producing hot water for both building heating and domestic hot water is seen in Figure 5.15.

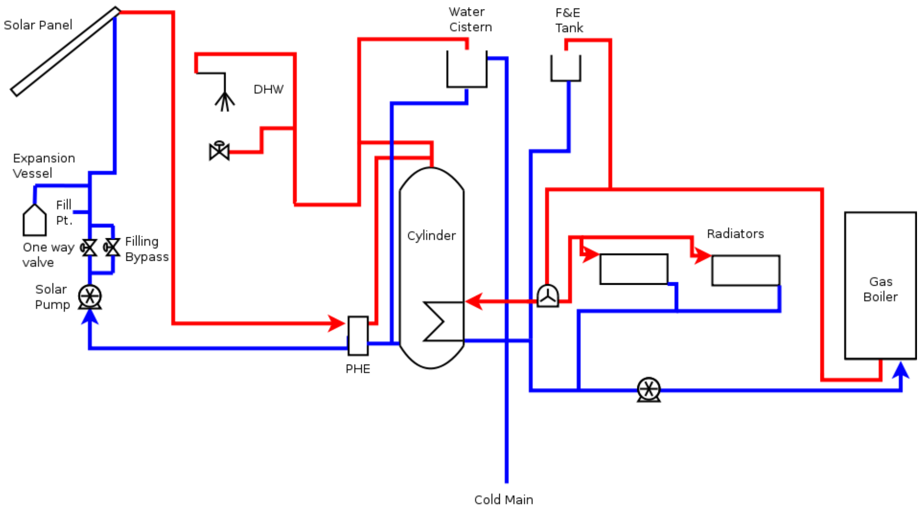

Figure 5.15 : The energy loop of solar assisted system producing hot water for both building heating and domestic hot water.

The technical properties of solar collectors are similar with ones used in the production of the sanitary hot water but in this application the amount of solar collector was increased and 102 solar collectors was placed in the south direction to the roof area of the case study building. Besides, the existing condensing boilers support the accumulation tanks used to ensure hot water to the building heating systems in this application. These tanks are used to store thermal energy of water ensured by solar collectors and existing boilers.

5.5.2.5 The effect of PV systems on building energy performance

In this application, the effect of PV panels on building energy efficiency are tested in order to save on electricity consumed by HVAC systems and 102 PV panels were placed in the south direction of the roof area of the case study buildings at regular intervals. The panel dimensions are showed Figure 5.16 below.

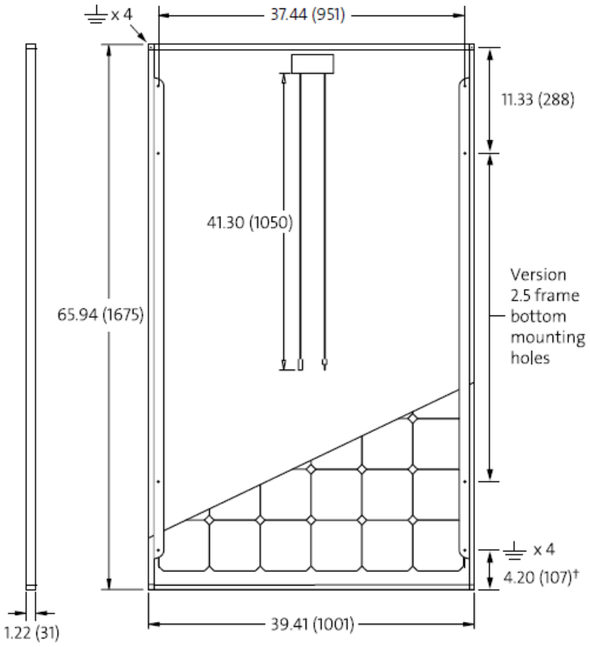

Figure 5.16 : The dimensions of PV panel (all units provided are imperial, SI units provided in parentheses).

This system operates on grid and the produced electricity is used to assist the electricity consumption lighting system. The cell type of panels is mono crystalline and the each panel consists of 60 cells. The technical properties of the panels are illustrated in Table 5.19.

Table 5.19 : The PV panel performance under standard test conditions (STC).

Maximum Power	P_{max}	280 Wp
Open Circuit Voltage	V_{oc}	39.5 V
Maximum Power Point Voltage	V_{mpp}	31.2 V
Short Circuit Current	I_{sc}	9.71 A
Maximum Power Point Current	I_{mpp}	9.07 A

*STC: 1000 W/m^2, 25 °C, AM 1.5

5.5.2.6 The effect of utilizing exhaust gas thermal energy of existing cogeneration system on building energy performance

In this retrofit measure, the new system was developed to support heating systems of case study building by utilizing exhaust gas thermal energy of existing cogeneration system which is used to produce electricity and sanitary hot water for Kanyon building. The technical data of existing coheneration system is seen in Table 5.20.

Table 5.20 : The operating parameters of existing cogeneration module.

Continuous output parallel with network			50% Load	75% Load	100% Load
Electrical output	cannot be overloaded	kW	200	300	401
High-temperature heat output	Tolerance 7%	kW	316	423	552
Low-temperature heat output	Tolerance 7%	kW	11	16	28
Fuel consumption (at Hi = 10 kWh/m^3)	Tolerance 5%	kW	609	831	1,053
Efficiency in parallel operation with network					
Electrical efficiency		%	32.8	36.1	38.1
High-temperature thermal efficiency		%	51.9	50.9	52.4
Low-temperature thermal efficiency		%	1.8	1.9	2.6
Total efficiency		%	86.5	88.9	93.1
Heat generation (heating)					
Return temperature in front of the module	min./max.	°C	60/70		
Standard temperature difference	max. return/forward flow	K	20		
Flow temperature	max.	°C	90		
Heating water flow	Standard	m^3/h	23.5		
Highest permitted operating pressure (high temperature)		bar	10		
Highest permitted operating pressure (low temperature)		bar	2		
Pressure loss at standard flow rate in module LT	Standard	bar	0.3		
Exhaust gas					
Exhaust gas volume flow, moist	at 120 °C	m^3/h	1,750		
Exhaust gas mass flow, moist		kg/h	2,200		
exhaust gas volume flow, dry	0 % O_2 (0 °C; 1012 mbar)	Nm^3/h	1,861		
maximum acceptable counter pressure	by module	mbar	15		
exhaust gas temperature	max.	°C	120		

Before this research, a new project was arranged by technical team of Kanyon building and the exhaust gas of existing cogeneration system was condensed so the thermal energy produced by condensation increases the energy efficiency in sanitary hot water production. However, it has been determined that the output temperature of the exhaust gas is about 101°C in the performance tests after the condensation. Besides, it is given that the flow rate of exhaust gas is 2,200 kg/h in technical documentation. After discussions with academicians and experienced mechanical engineers in the sanitary engineering sector, it has been thought that this temperature can still be a high and beneficial thermal source. It was aimed to reduce the annual heating consumption of case study building by utilizing the thermal energy of cogeneration system exhaust gas to preheat the boiler water. The existing cogeneration system used to generate hot water and electricity in Kanyon is shown in figure 5.17. For the application of new system, an air to water heat exchanger with necessary capacity was selected and the extracted thermal energy by using this heat exchanger was used to support accumulation tank that stored hot water to heating the building by using circulation pumps.

Figure 5.17 : The view of existing cogeneration system in case study building.

In Table 5.20 and Table 5.21, the technical peroperties are summarized for all standard and advanced retrofit measures applied to the buildings' mechanical systems to increase the energy efficiency of the building.

Table 5.21 : The standard retrofit measures.

Standard Measures	Design Parameters	Capacity and Efficiency
Heat Recovery Unit	- Sensible heat eff.	75% – Sensible heat
	- Sensible and latent heat eff.	75% – Sensible heat 50% – Latent heat
Economizer	- Max. outdoor air temp.: 21°C	-
	- Max. out. air enthalpy: 53 kJ/kg	-
Radiant Heating System	- Boiler oprt. temp.: 50/30°C	Heating capacity: 320 kW
	- Floor control temp.: 28°C	
Chilled Ceiling System	- Chiller oprt. temp.: 10/12°C	Cooling capacity: 200 kW

Table 5.21 (continued) : The standard retrofit measures.

Standard Measures	Design Parameters	Capacity and Efficiency
Ground Source Heat Pump	- 1st CS: Amount of boreholes: 120 - 2nd CS: Amount of boreholes: 60 - Depth of boreholes: 76 m	Heating capacity: 778 kW Cooling capacity: 350 kW
Heat Recovery Ventilator	- Fan flow rate of system equals to zone fresh air need	Fan efficiency: 70%
Mechanical Ventilation System Dependent on Occupant Density	- Fan frequency converter	-

Table 5.22 : The advanced retrofit measures.

Standard Measures	Design Parameters	Capacity and Efficiency
Cogeneration System	- Jacket cooling water: 80/60°C	1st CS: Both heating and elect. power capacity: 500 kW 2nd CS: Both heating and elect. power capacity: 400 kW
Trigeneration System	- Jacket cooling water: 80/60°C - Abs. chiller oprt. temp.: 7/12°C	1st CS: Both heating and elect. power capacity: 500 kW 2ndCS: Both heating and elect. power capacity: 400 kW Cooling capacity of abs. chiller: 250 kW
Hybrid Ventilation	- Min. out. air enthalpy: 35 kJ/kg - Max. out. air enthalpy: 53 kJ/kg	2 ach for each zone
Solar Assisted Sanitary Hot Water Production System	- 45 solar collectors - Collector area: 2.5 m^2 - 4 lt hot water tank	Tank efficiency: 80%
Solar Assisted Building Heating System	- 102 solar collectors - Collector area: 2.5 m^2 - 1st CS: 20 lt hot water tank - 2nd CS: 20 lt hot water tank	Tank efficiency: 80%
PV System	- 102 PV panels - Panel area: 1.6 m^2 - DC converter	-
Utilizing Exhaust Gas Thermal Energy of Existing Cogeneration System	- Exhaust gas temp.101°C - Exhaust gas flow rate: 2200 kg/h	Heating capacity: 498 kW Elec. power capacity: 363 kW

5.6 Calculation of Primary Energy Consumption of Retrofit Measures Applied to First Case Study Buildings

All standard and advanced retrofit measures in the tables above was applied as a single measure to the case study building energy model and the effects of these retrofits on building energy performance under the climate data of Istanbul was tested. Then, the annual energy consumption results in terms of kWh for each measure are converted to primary energy using energy conversion coefficients. In Figure 5.18, the annual energy consumption of renovated buildings by applying single measures is divided into consumption groups as heating, cooling, interior lighting, fans and pumps and the change in primary energy consumption of these groups by applying of each single measure. All the standard and advanced retrofit measures mentioned previously are applied to the existing building; but only the measures that increase the energy efficiency of the first case study building are shown Figure 5.18. In Table 5.23, the description of single measures (SM) seen in Figure 5.18 are explained in detailed. The details of energy improvement results are explained for each applied single measure.

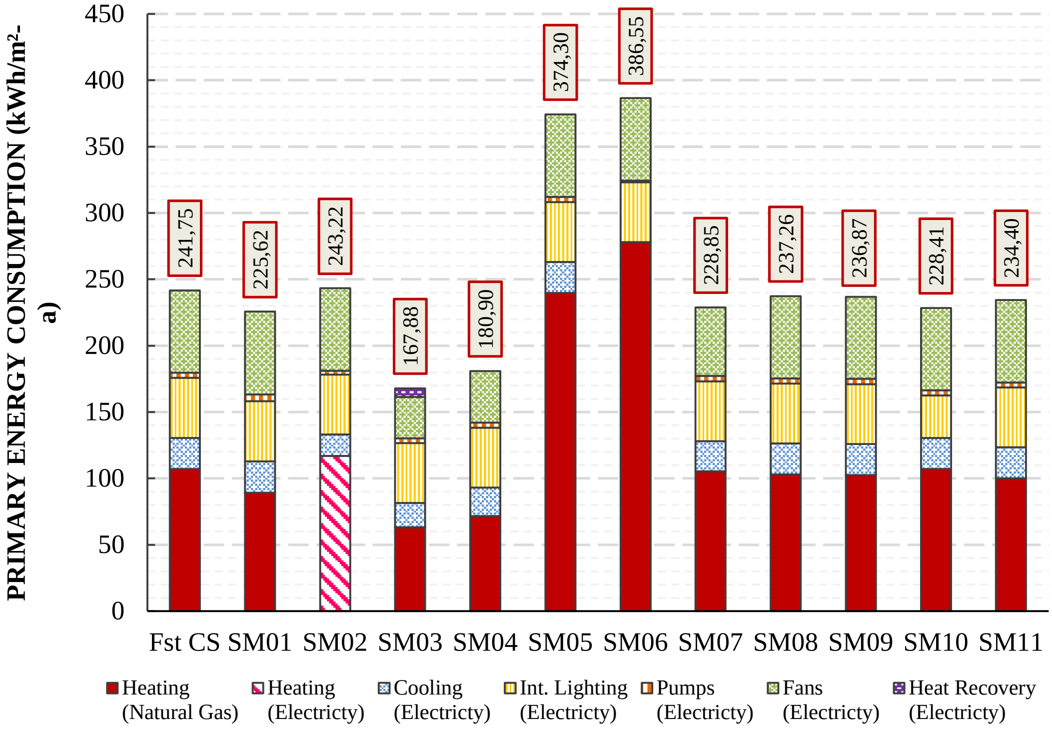

Figure 5.18 : The annual primary energy consumption calculated by dividing into consumption groups of first case study building (Fst CS) and the single measures applied to the first case study building (SM).

Table 5.23 : The applied single measures to first case study building.

Single Measures	Description
Fst CS	First Case study building
SM01	Radiant heating system
SM02	Ground source heat pump
SM03	Heat recovery ventilator
SM04	Mechanical ventilation system dependent on occupant density
SM05	Cogeneration system
SM06	Trigeneration system
SM07	Hybrid ventilation
SM08	Solar assisted sanitary hot water production system
SM09	Solar assisted building heating system
SM10	PV system
SM11	Utilizing exhaust gas thermal energy of existing cogeneration system

All the standard and advanced retrofit measures mentioned previously are applied to the existing building; but only the measures that increase the energy efficiency of the first case study building are shown Figure 5.18. The details of energy improvement results are explained below for each applied single measure.

- The results of the building energy performance analysis show that heat recovery units with different efficiencies within the air handling unit have no effect on the energy performance of the first case study building. The first case study building is a residential building and the heat gains from the lighting loads, electrical equipment and occupants in residence units are low. In addition, the fresh air requirement of a residential building is lower compared to other building types. Therefore, the return air temperature is not high enough to condition fresh air coming from outdoor. As a result, it was found that the using of heat recovery unit in air handling units does not affect the energy performance of this first case study building so this measure is not included in the single measures shown in Figure 5.18.
- In this study, it has been found that the use of the economizer is not an effect on the energy efficiency of first case study building although the economizers which have different control types have been used in air handling units. Looking at Table 5.16, it is seen that the annual cooling consumption is well below the annual heating consumption. The cooling demand of this building is very low due to construction properties, low heat gains and being a residential building. Although the outdoor air provides the desired climatic conditions in cooling seasons, it is understood that the indoor air temperature in residence units is not quite high to utilize the cooling effect of the economizer. For this reason, this measure is not also included in the single measures shown in Figure 5.18.
- The effect of the radiant heating system on the energy efficiency of the building was analyzed instead of the radiator heating system in first case study building. It is known that the applications of radiant heating system provide higher efficiency at low boiler operating temperatures. For this reason, the boiler operating temperature has been reduced from 70/50°C to 50/30°C in this retrofit measure. As a result, when compared with the first

case study building results, annual heating consumption improved by 17.81 kWh/m^2.

- The effect of ground source heat pump (GSHP) system on the energy efficiency of the first case study building was tested instead of existing heating and cooling system. It is understood that the designed capacities of GSHP system, the amount of boreholes and the length of boreholes are sufficient in order to ensure the required set-point temperatures and occupant thermal comfort in first case study building. However, it is seen that the annual heating consumption of renovated building by using GSHP system is as higher as 9.85 kWh/m^2 compared to the existing building annual heating consumption according Figure 5.18. Besides, the GSHP is forced to produce hot water at 70°C in order to heat renovated building via radiator systems. The thermal energy extracted from the earth is quite high but limited. For this reason, it possible to meet the buildings' heating demand efficiently when the GSHP system should be used with a system that operates at lower operating temperature compared to radiator system.
- The heat recovery ventilator (HRV) was used for each residence unit instead of constant flow rate and fully fresh-air air handling units to supply required fresh air in first case study building. Looking at the test results in Figure 5.18, it is seen that there is an apparent difference between first case study building and this renovated building when compared their annual heating and fan primary energy consumptions. The reason of high reduction of 31.1 kWh/m^2 in fans is providing fresh air to each residence by utilizing HRV that uses fan operated by lower engine power. The reason of decline of 43.97 kWh/m^2 in heating is conditioning the fresh air by utilizing exhaust air thermal energy via heat exchanger in HRV without using heating coil. Furthermore, looking at Figure 5.18, it is distinguished that a new consumption subgroup comes up as heat recovery which consumes 2.8 kWh/m^2 of electricity in this retrofit unlike the other renovated building. However, it is understood that the contribution of HRV system usage to the energy improvement is considerably high considering the annual energy consumption of this renovated building.
- Another single measure is that the required fresh air is given to each residence unit depending on occupant density. For this application, a building

automation system is used which controls the air handling unit fans. When the simulation results are analyzed, it is seen that the sum of heating, cooling and fan annual consumption decreased by 59.72 kWh/m^2 and the annual total primary energy consumption reduced considerably. Therefore, the fresh air requirement for occupant health was continued to supply to each residence unit and it was saved on annual energy consumption considerably by applying of this measure.

- The simulation test results of cogeneration and trigeneration system designed to improve the energy efficiency of first case study building are seen in Figure 5.18. These systems that operate by using natural gas are used for heating, cooling the building and producing sanitary hot water during the year. Also, these systems produce electricity during their working process. The electricity generation of these systems in terms of primary energy is shown in Figure 5.19. Looking at this figure, it is understood that the amount of annual electricity production of these systems is quite higher than annual electricity consumption of both cogeneration and trigenearation system retrofit measures seen in Figure 5.18.

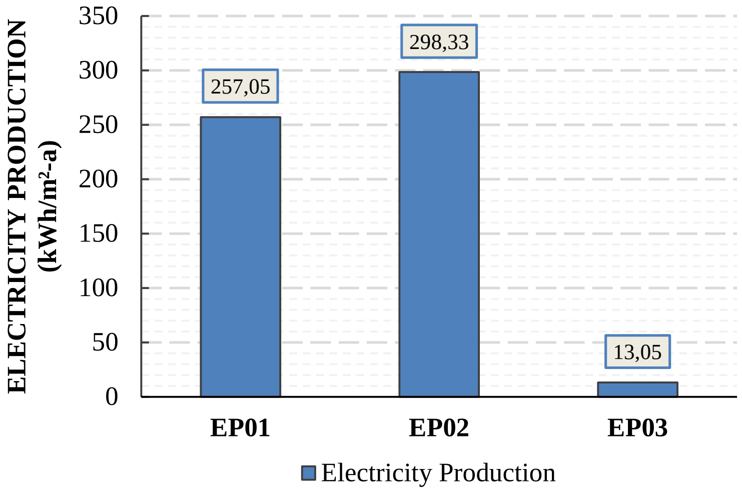

Figure 5.19 : The amount of electricity production in terms of primary energy by using cogeneration system “EP01”, trigeneration system “EP02” and PV system “EP03”.

In Turkey, the Ministry of Energy and Natural Resources published a regulation entitled “Elektrik Piyasasında Lisanssız Elektrik Üretimine İlişkin Yönetmelik” (Unlicensed Electricity Generation in Electricity Market Regulation) [85] in Resmi Gazette on 10/02/2013 and this regulation are included prohibitions, restrictions and sanctions related to electricity production for residential buildings. Accordingly, in the 3th paragraph of Article 28, “Within the scope of this Regulation, the electricity generated in the production facilities can not be used to a commercial activity except for the exceptions stated in this Regulation and it can not be offered for consumption outside the distribution area where the production facility is located." The electricity generated at residential buildings in Turkey was considered as unlicensed production. According to this regulation:

- The micro cogeneration facility is a facility that the total installed capacity based on electrical energy is 100 kW and less.
- The maximum installed capacity is 1 MW for the facilities that produce electricity by using wind and solar energy sources except the applications on roof according to subparagraphs (c) of 1st paragraph of Article 5.
- Within the scope of subparagraphs (a), (b), (d), (d), (f) and (g) of 1st paragraph, there is no upper limit related to installed capacity for the electricity production facilities except the facilities mentioned above.

Considering this regulation, the total capacity of cogeneration and trigeneration system applied as retrofit measures in this study is higher than 100 kWe and the wind and solar energy sources are not used in these systems. Therefore, these retrofit measures in this study are included in the facilities that have no upper limit of installed capacity. However, within the scope of prohibitions and sanctions mentioned above, the electricity produced in these types of building has to be used in the building where production facility is located and it has not to be consumed and sold outside this building. Looking at Figure 5.18 and Figure 5.19, the annual electricity generations by using these systems are higher the annual electricity consumptions in renovated buildings and the excess electricity is not used in these buildings. Therefore, the usage of cogeneration and trigeneration systems applied for this study is not possible due to prohibitions, restrictions and sanctions in the regulation. That’s why, the usage of these CHP systems are not included in the further steps of this research.

- In hybrid ventilation retrofit measure, the operable windows are controlled by using window actuator systems that are electrical mechanisms control the windows in accordance with the certain enthalpy range of the indoor and outdoor air. These mechanisms communicate with a building automation system and when the windows are opened, the automation system closes the blower fans by communicating with the existing air handling units. In this first case study building, the natural and mechanical ventilation are used together so the hybrid ventilation is used in this building for getting required fresh air. Looking at the test results, there is a remarkable reduction in the fan annual energy consumption of renovated building. There is also reduction in the annual heating and cooling consumption of this renovated building because the supplied fresh air is conditioned by AHU coils when the windows are closed but the BAS stops the AHU coils when the windows are opened and the interior spaces are naturally ventilated.
- Looking at the test results of the single measure that is sanitary hot water production supported by solar energy, it is seen that the annual heating consumption decreases by 4.17 kWh/m^2. In this retrofit application, the solar collectors are placed in the roof area of the elevator machinery room where the solar radiation is utilized most efficiently and the shading effect is less. This roof area does not allow to more solar collectors to be installed but this single measure contributes to the reduction of natural gas consumption by assisting to produce sanitary hot water.
- A system design was made to support both building heating system and sanitary hot water production system assisted by solar energy. In this single measure, the number of solar collectors was increased so the other roof areas were also used which is less solar radiation and more shading effect. When the test results were analyzed, it is seen that this retrofit measure ensures lower energy improvement such as 0.36 kWh/m^2 compared to the measure applied for sanitary hot water production mentioned above. There is more than one reason for explaining this result. Firstly, even if the solar collector number was increased, the sunshine duration of climate zone in which the first case study building is located is not long enough compared to hot-humid climate zones in the southern region of Turkey to be utilized the solar energy

for heating of the buildings. Besides, in this climate zone the solar radiation intensity falling on a surface is less than hot-humid climate zones. Secondly, the amount of solar energy decreases due to the shading effect in the other area of roof so the energy efficiency of the system is also decreasing for producing the required hot water. Furthermore, the utilizing of solar energy for supporting building heating system is more efficient by using the radiant heating system which operates at lower operating temperatures compared with radiator system in first case study building. Due to these reasons, it is understood that the heating consumption has not been saved as much as thought by using solar energy assisted heating system for supporting building heating systems in this single measure application.

- The simulation test results were analyzed the effect of PV systems on building energy efficiency. When these results are analyzed, it is determined that there is a reduction in annual cooling and fan consumption because the PV panels placed in the roof area became like the shading surfaces and declined to the cooling demand of building. Thus, the cooling system in renovated building consumed as less energy as 0.38 kWh/m^2. Looking at Figure 5.19, it is seen that the annual electricity generation is 13.05 kWh/m^2 by using PV systems and in this study, it is assumed that this amount of generated electricity energy is used to support for the lighting system in this building. As a result, when the amount of generated electricity and the energy saving in cooling consumption is summed the net annual energy consumption becomes 13.43 kWh/m^2 in this renovated building.
- In this retrofit application, the exhaust air thermal energy of existing cogeneration system that uses in order to produce sanitary hot water and generate electricity in Kanyon was utilized. It has been determined that the application of this improvement measure saves 8.35 kWh/m^2 of annual natural gas consumption for heating. When looked at this result, it is seen that, the heating energy obtained from the exhaust air of cogeneration system is a limited source for this first case study building but becomes a thermal resource without paying any price.

The effects of standard and advanced retrofit measures on first case study building were analyzed above and the reasons and results affected energy improvement were explained in detail. After these analyzes, while creating the energy improvement packages by combining each single measure with each other's, it was thought that the testing of energy performance of many combinations will cause loss of time and quality. For this reason, it has been decided to analyze only the packages that are combination of the measures that are compatible in terms of their technical system properties and high efficient. It is also thought that a graph consists of fewer and more efficient results, is less complex and more understandable. In Figure 5.20, the annual energy consumptions of retrofit packages in terms of primary energy consumption are demonstrated. In Table 5.24, the description of packages (P) seen in Figure 5.20 are explained in detailed.

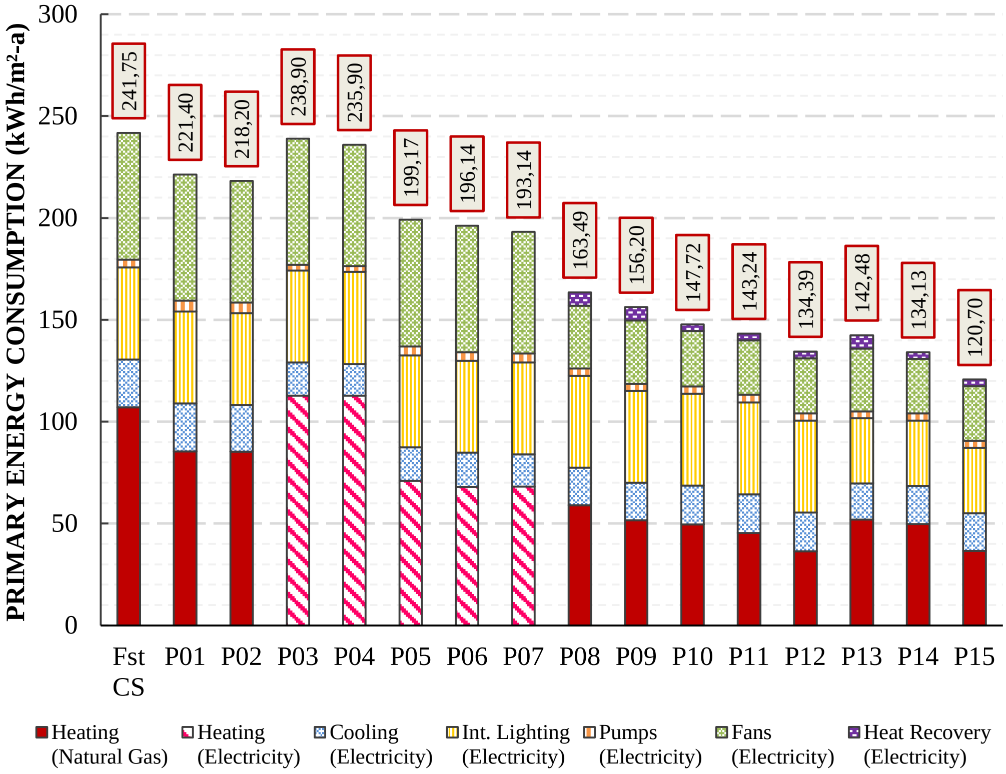

Figure 5.20 : The annual primary energy consumption calculated by dividing into consumption groups of first case study building (Fst CS) and the packages applied to the first case study building (P).

Table 5.24 : The applied packages to first case study building.

Packages	Description
Fst CS	First Case study building
P01	The utilizing radiant heating system and solar assisted sanitary hot water production system
P02	The utilizing radiant heating system, solar assisted sanitary hot water production system and hybrid ventilation system
P03	The utilizing ground source heat pump and solar assisted sanitary hot water production system

Table 5.24 (continued) : The applied packages to first case study building.

Packages	Description
P04	The utilizing ground source heat pump, solar assisted sanitary hot water production system and hybrid ventilation system
P05	The utilizing ground source heat pump and radiant heating system
P06	The utilizing ground source heat pump, radiant heating system and solar assisted sanitary hot water production system
P07	The utilizing ground source heat pump, radiant heating system, solar assisted sanitary hot water production system and hybrid ventilation system
P08	The utilizing heat recovery ventilator and solar assisted sanitary hot water production system
P09	The utilizing heat recovery ventilator and exhaust gas thermal energy of existing cogeneration system
P10	The utilizing heat recovery ventilator and mechanical ventilation system dependent on occupant density
P11	The utilizing heat recovery ventilator, mechanical ventilation system dependent on occupant density and solar assisted sanitary hot water production system
P12	The utilizing heat recovery ventilator, mechanical ventilation system dependent on occupant density and exhaust gas thermal energy of existing cogeneration system
P13	The utilizing heat recovery ventilator, exhaust gas thermal energy of existing cogeneration system and PV system
P14	The utilizing heat recovery ventilator, mechanical ventilation system dependent on occupant density and PV system
P15	The utilizing heat recovery ventilator, mechanical ventilation system dependent on occupant density, exhaust gas thermal energy of existing cogeneration system and PV system

When the simulation results are analyzed, it is seen that the P01 package saved on considerable energy in annual heating consumption. After the application of the P02 package, an energy consumption reduction was observed in heating similar to P01 but there was a fewer energy saving on annual fan consumption by using hybrid ventilation strategy. With this application, the annual fan consumption decreased by only 1.05 kWh/m^2. The reason of this result is that the annual cooling demand of this residential building is not high enough in order to ensure high energy saving by utilizing the hybrid ventilation based on enthalpy control especially in transition seasons of Istanbul climate. Looking at the results of the P03 and P04 packages, it is seen that the ground source heat pump increased the heating consumption although it was used with hybrid ventilation and solar assisted sanitary hot water production system that enhanced the building energy efficiency. Although the annual heating consumption of GSHP in terms of kWh is lower than the annual heating consumption of existing heating system in first case study building, the fact that this system consumed electricity to extract the thermal energy from the earth increases the primary energy consumption in heating. This reason increased the heating energy consumption in packages P03 and P04. Furthermore, in these packages, the GSHP systems were forced to produce hot water at 70°C by extracting the thermal energy from the earth to support the radiator system in first case study building that’s why the energy efficiency of GSHP systems reduced. It is known that the ground source heat pump operates at higher efficiency when used with a system operating at lower operating temperatures, such as a radiant heating system. For this reason the packages P05, P06 and P07 were created. Looking at the results of these packages, it is understood that the radiant heating system operating at 50/30°C improves the energy efficiency of GSHP system and these packages reduced the annual primary energy consumption between 36 and 39 kWh/m^2 in heating. However, it should be decided whether the GSHP systems are feasible for this retrofit packages after considering the required drilling, labor and system maintenance costs of the boreholes to be opened for this residential building. When the results of the packages in which the fresh air required for each residence unit was supplied by using heat recovery ventilators instead of the existing air handling units are analyzed, it is seen that the improvements are quite high in annual fan and heating energy consumption between P08 and P15 packages. When the annual primary energy consumptions of these packages are compared to others, it is clear that the annual energy savings on the fan consumption play a major role in reducing the total primary energy consumption of the packages between P08 and P15. When the package P12 is compared to P15, it is understood that the contribution of P15 package to the building's annual energy savings is higher due to generating electricity by using PV system. As a result, the P15 became the most energy efficient package compared to all other single measures and packages by ensuring highest energy improvement for first case study building.

5.7 The Calculation of Global Costs of First Case Study Building

Although the applied retrofit measures increased the energy efficiency of the building, it is just possible to determine whether the applied systems are feasible for the case study building after calculating the system costs. Therefore, the global cost of each renovated building must be calculated by using the net present value methodology throughout 30 years economic life determined by EPBD-recast for residential buildings. In Table 5.25, the global cost of case study building and renovated buildings that were retrofitted by utilizing single measures and packages are demonstrated. Cost calculations were done by using the calculation sheet showed in Appendix A.

Looking at the table, it is seen that the radiant heating system, SM01, and the ground source heat pump, SM02, increased the global costs of renovated buildings compared to the global cost of case study building. Although the radiant heating system seems more applicable in terms of maintenance, repair and energy costs than the radiator system, the initial investment cost is much higher than the radiator system. Looking at calculations, it was seen that the initial investment costs of radiator system was 5.16 TL/m^2 and the initial investment costs of radiant heating system was 171.48 TL/m^2.

Table 5.25 : The global cost of first case study building and renovated buildings.

Retrofit Measures	Global Costs (TL/m^2)
Fst CS	540.46
SM01	763.87
SM02	985.63
SM03	465.25
SM04	430.07
SM07	567.74
SM08	547.08
SM09	572.64
SM10	535.36
SM11	542.55
P01	770.75
P02	817.58
P03	989.42
P04	1,035.04
P05	1,136.58
P06	1,143.83
P07	1,191.08
P08	472.01
P09	460.29
P10	429.83
P11	436.45
P12	422.32
P13	454.15
P14	424.07
P15	416.41

Although the initial investment cost of GSHP is not very expensive, the initial investment cost of drilling process which is essential in order to extract thermal energy from the earth and labor cost are so much expensive. The initial investment cost of drilling process is just 363.4 TL/m^2. In addition, the GSHP system uses electricity instead of natural gas for heating of the building which significantly increases the energy costs of the system. According to table, the heat recovery ventilator, SM03, and the mechanical ventilation system dependent on occupant density, SM04, reduce the global costs. Both the maintenance cost and the initial investment cost of these systems are very low during 30 years and these systems reduced the energy costs in the life cycle substantially considering the annual primary energy consumption. Looking at the global cost of hybrid ventilation system, SM07, the summation of initial investment cost of window actuator mechanisms and the building automation system are 40.17 TL/m^2 but this system is inadequate to reduce the energy costs because the cooling demand of case study building is not high enough in the warm - humid climate zone. When the global costs of solar assisted systems are analyzed, SM08 and SM09 is not as sufficient as to reduce the heating energy costs due to the low production of sanitary hot water based on occupant density in residential building types. Besides, these systems used to support the existing heating system of case study building operate at low efficiency due to lack of solar radiation and less sunshine duration in the climate zone in which the case study building is located. While the heating cost of the case study building is 165.55 TL/m^2, the heating costs of SM08 and SM09 are 159.11 TL/m^2 and 158.55 TL/m^2 respectively. The initial investment cost of the PV system used in SM10 is 22.55 TL/m^2. When it is assumed that the generated electricity by using PV systems is used to support the energy demands of lighting systems in the building, the annual electricity saving on the consumption of these systems is 29.15 TL/m^2. In addition, the cooling cost was reduced by 0.21 TL/m^2 due to the shading effect since the PV panels were used in the entire area of roof. When the global cost of the system that supports the existing heating system of case study building by utilizing the exhaust gas thermal energy of existing cogeneration system is analyzed, SM11, the summation of initial investment cost of heat exchanger, accumulation tank and circulation pumps that required for designing this system is 32.56 TL/m^2. This system achieved to reduce both the annual heating energy cost by 10.88 TL/m^2 and the annual electricity consumption by the fans and pumps by 0.67 TL/m^2. However, maintenance and repair of the accumulation tank and circulation pumps added additional cost to the system. Especially, the high capacity of the selected accumulation tank increased the initial investment cost of the system. For this reason, the global cost of the renovated building in which this system is used is higher 2.09 TL/m^2 more than the global cost of the existing building.

5.8 Identification of Cost-Optimum Energy Efficiency Level of First Case Study Building

Annual primary energy consumptions and global costs of all renovated buildings that are retrofitted by applying retrofit measures are compared simultaneously to determine the cost-optimum efficiency level. This comparison is showed at Figure 5.21. Accordingly, the measure that optimizes the case study building by optimizing it in terms of energy and costs will determine the cost-optimum energy efficiency level of the building. When looked at the figure, the red dashed line intersects with Fst CS that represents the annual primary energy consumption and global cost during economic life cycle of the first case study building.

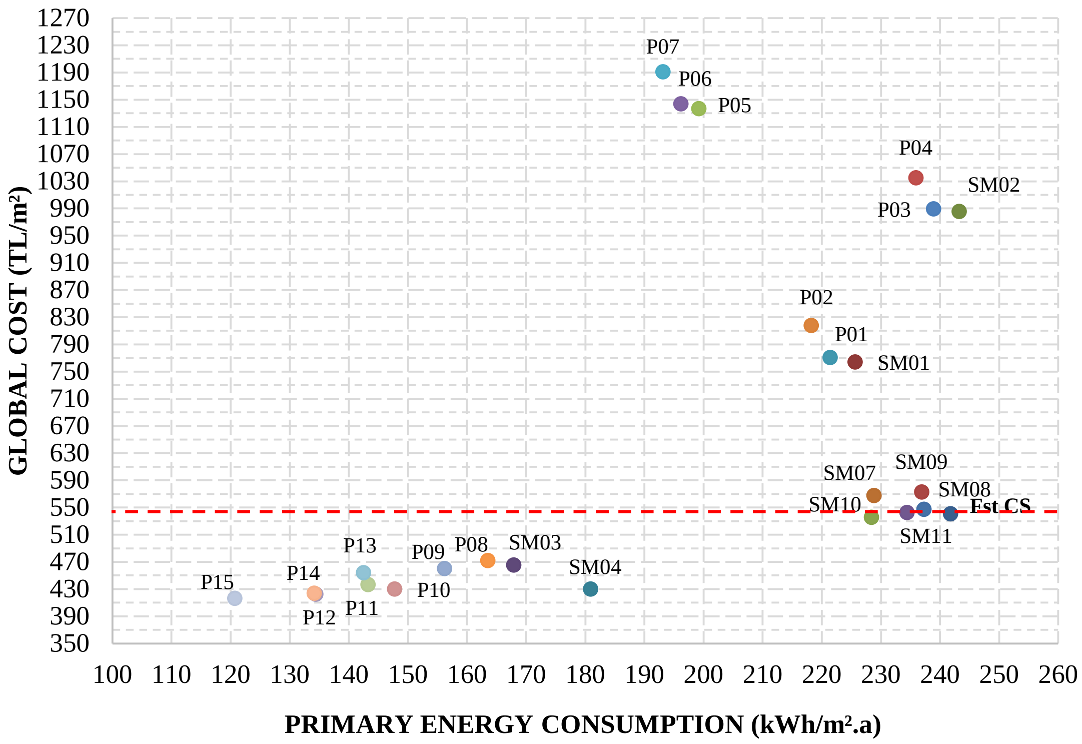

Figure 5.21 : The comparison between global costs and annual primary consumptions of the first case study building and renovated buildings.

The retrofit measures over this line increase the global cost despite reducing the annual energy consumption of the building. Accordingly, the single measures and packages represents the ground source heat pump and radiant heating system increases the building energy efficiency but these systems also raise the global costs due to fact that the initial investment costs of these systems are still high in Turkey. In particular, P05, P06 and P07 are the improvement packages which the radiant heating system is supported by the ground source heat pump system. Even though the using of GSHP with radiant heating system that operates at low operating temperature reduces the energy costs considerably, the initial investment cost of both systems increase the global costs of these retrofit packages extremely. The global cost and energy consumption of SM07, SM08 and SM09 which represents the hybrid ventilation, solar assisted sanitary hot water production and solar assisted building heating which their initial investment costs are less was also compared. These measures raise the global cost although they reduce the annual energy consumption of renovated buildings owing to the less cooling demand of this residential building and the warm - humid climate zone where the case study building is located. For supporting the existing heating system, the utilizing of exhaust gas thermal energy of existing cogeneration system, SM11, increased the global cost of the building just 2.09 TL/m^2 during the economic life cycle. However, in the applications that higher exhaust gas thermal energy, the global cost difference between the case study building and this renovated building may decreases, moreover the global cost of this renovated building may become fewer than the case study buildings'. Looking at the results of SM10 that represents the electricity generation by PV systems, it is seen understood that these system reduced the global cost of the building by 5.1 TL/m^2 and it improves the annual primary energy consumption by 13.43 kWh/m^2. If the installations of PV system were promoted for the less initial investment cost by publishing new energy regulations by government in Turkey, it would be possible more electricity generation and less global cost by using these systems.

When the retrofit measures under the red dashed line are analyzed, it is seen that SM03 and SM04 reduce the global costs crucially by ensuring high amount of energy saving without compromising the thermal comfort of occupants. The reason of this, SM03 and SM04 measures that reduced the annual energy consumption of the building remarkably decreased the global cost by minimizing the energy costs during economic life cycle. Looking at Figure 5.21, it is seen that each packages that consist of these single measures reduces both the global cost and the annual primary energy consumption of renovated building significantly. However, the most crucial reduction was obtained by applying P15 package. In this package, SM11 that represents utilizing exhaust gas thermal energy of existing cogeneration system was also combined with other single measure mentioned above. After the applying of

SM11 to first case study building, it was established that this system raised the global cost slightly but when this single measure were used with SM03 and SM04 measures, the annual heating energy reduces significantly since there is no need to use heating energy in order to condition required fresh air by using heat recovery ventilator. Therefore, the contribution of the exhaust gas thermal energy to the annual heating consumption of the building increased. This result caused to reduce the global cost of the system by more decreasing the energy cost consumed for heating during the long-term.

When looked at the Figure 5.21, P12 package also includes SM03, SM04 and SM11 single measures that improve both primary energy consumption and global cost remarkably. Similarly P14 package is very close to P12 in terms of both primary energy consumption and global cost. In P14 package, the application of PV system was included instead of the utilizing exhaust gas thermal energy of existing cogeneration system. It was seen that all these single measures that utilized the heat recovery ventilator, mechanical ventilation system dependent on occupant density, exhaust gas thermal energy of existing cogeneration system and PV system developed the building energy performance in respect to energy and cost dramatically during the first case study buildings' economic life. Therefore, it has been decided to create a package in which these single measures are used together. Consequently, P15 is the most energy efficient retrofit package for the first case study building that represents the luxury high-rise residential building type in Turkey. Moreover this package is cost-optimum retrofit measure for the first case study building in this research.

5.9 Sensitivity Analyzes for First Case Study Buildings

In this approach, the impact of economic indicators were investigated which vary based on specific economic activities such as gross national product (GNP), unemployment rates, interest rates and etc. For the boundary conditions explained below, changes in the results of cost-optimal analyses were examined.

Sensitivity analyses on economic indicators focused on the real discount rate (R_d) as required by EU Regulation. According to Directive 2010/31/EU, the Regulation requires Member States to perform at least a sensitivity analysis on different price scenarios for all energy carriers of relevance in a national context, plus at least two scenarios each for the discount rates to be used for the macroeconomic and financial cost optimum calculations. For the sensitivity analysis on the discount rate for the macroeconomic calculation, one of the discount rates shall be set at 3% expressed in real terms. Member States have to determine the most appropriate discount rate for each calculation once the sensitivity assessment is performed. This is the one to be used for the cost-optimal calculation [86].

The global cost calculations in the first phase considered the average rates of previous years and assumed the discount rate (R_d) as 5.78%. Sensitivity analyses conducted in this second phase focused on this rate. The selection procedure considered the requirements of EU regulation and selected one of the analyzed discount rates as 3%. Accordingly, the rate which is higher than the existing assumption is 9% in the analyses.

In this research, the specified retrofit measures were analyzed in order to observe how these measures are affected by the variation of discount rate. Looking at the Figure 5.21, the measures that are close to first case study building in respect to both global cost and primary energy consumption were analyzed. It was desired to investigate whether the change in discount rate would reduce the global cost of these retrofit measures below the global cost of the first case study building. The single measures that labeled as SM07, SM08, SM09, SM10, SM11 (hybrid ventilation, solar assisted sanitary hot water production system, solar assisted building heating system, PV system, utilizing exhaust gas thermal energy of existing cogeneration system respectively) are analyzed and the results compared with each other in terms of impact to cost-optimum level of first case study building. Moreover, the packages P13, P14 and P15, including the PV system, were also included in the sensitivity analyzes. Referring to Figure 5.21, it has been determined that the measure of cost-optimum efficiency level of the first case study building is P15 package. However, both the annual primary energy consumption and global cost of the P12 package is higher than P15. Unlike P15 package, the PV system application was excluded from P12 package. Therefore, it is desirable to investigate how these packages, including PV system applications, are affected by the change in the discount rate.

The results of the sensitivity analyzes of the measures applied to the first case study building are shown in the graphic below. Referring to Figure 5.22, the blue dashed line represents the scenario in which global costs are calculated by assuming a discount rate of 3%. The red dashed line and green dashed line also represents the scenario in which global costs are calculated by assuming a discount rate of 5.78% and 9% respectively. Looking at the blue dashed line, it is seen that the discount rate of 3% did not reduce the global cost of SM07, SM08 and SM09 below the global cost of first case study building. Similarly, looking at the green dashed line, when the global cost of these single measures were calculated considering discount rate of 9%, the global cost of first case study building seems to be still higher than these retrofit measures. Looking at Figure 5.21, it can be seen that the global cost of SM10 and SM11 is slightly lower than the global cost of the first case study building. However, in the scenario which the discount rate is 5.78%, the global cost of the first case study building is higher than SM10 by 5.10 TL/m^2 but lower by 2.09 TL/m^2 from SM11. The reduction of the discount rate has reduced the global cost of these measures by slightly more than the global cost of the first case study building. In the scenario which the discount rate is 3%, the difference between the global cost of the first case study building and the global cost of the SM10 has increased by 15.91 TL/m^2 and the global cost of the SM11 has come close to the global cost of the first case building and the difference has decreased to 0.51 TL/m^2.

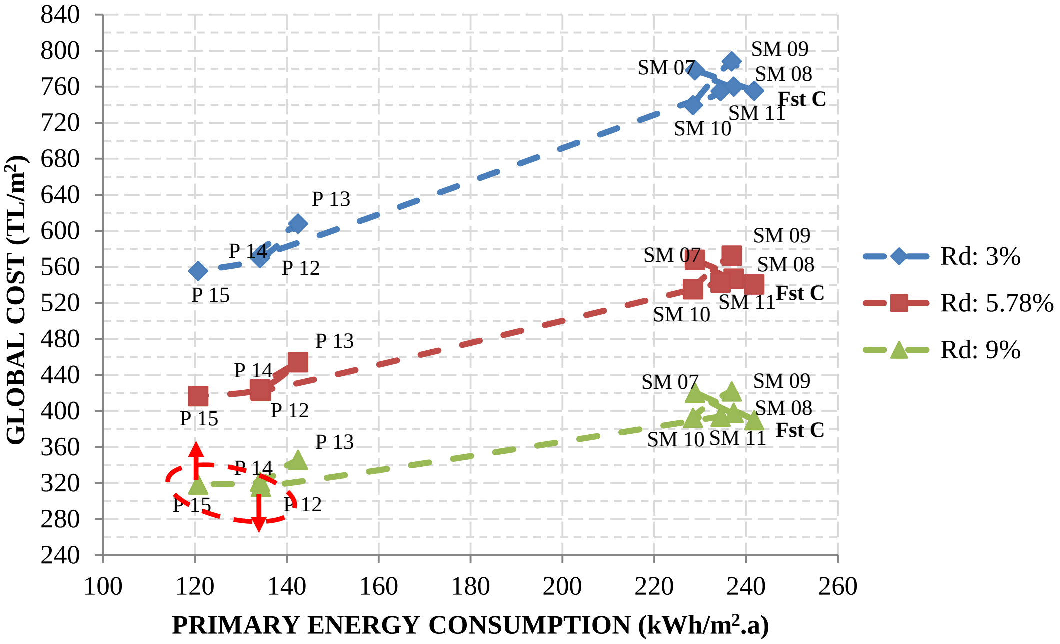

Figure 5.22 : The variation of global costs of measures applied to the first case study building.

Increasing the discount rate has increased the global cost of these measures and raised the global costs of these measures above the global cost of the first case study building. In the scenario which the discount rate is 9%, the global cost of the SM10 is 2.39 TL/m^2 higher than the global cost of the first case study building. The global cost of SM11 is 3.79 TL/m^2 higher than the global cost of the first case building. When looked at the packages, in the scenario which is the discount rate of 3%, the global cost difference between first case study building and P15 has raised by 200.08 TL/m^2. This global cost difference is 124.05 TL/m^2 in the scenario which is the discount rate of 5.78%. In both these scenarios, P15 goes on being cost-optimum energy efficient measure of first case study building. However, it is seen that the cost-optimum energy efficiency level changed with a slight difference when the discount rate has been raised to 9%. When the global cost difference between P15 and first case study building is 71.7 TL/m^2, this difference is 73.93 TL/m^2 between P12 and first case study building. According to this result, the using of PV systems in this residential building type has increased the global cost of P15 when the discount rate has been raised to 9%. The reason for this result is that the energy, running and maintenance costs of this system keep constant while initial investment costs are reduced. Therefore, keeping constant of these costs has enhanced the global cost during the long term and P12 becomes a cost-optimum energy efficient measure when the discount rate is 9% in this study.

5.10 Calculation of Primary Energy Consumption of Retrofit Measures Applied to Second Case Study Buildings

All standard and advanced retrofit measures in the tables above was applied as a single measure to the second case study building energy model and the effects of these retrofits on building energy performance under the climate data of Istanbul was tested. Then, the annual energy consumption results in terms of kWh for each measure are converted to primary energy using energy conversion coefficients. In Figure 5.23, the annual energy consumption of renovated buildings by applying single measures is divided into consumption groups as heating, cooling, interior lighting, fans, pumps and heat recovery and the change in primary energy consumption of these groups by applying of each single measure.

All the standard and advanced retrofit measures mentioned previously are applied to the existing building; but only the measures that increase the energy efficiency of the second case study building are shown Figure 5.23. The details of energy improvement results are explained below for each applied single measure. In Table 5.26, the description of single measures (SM) seen in Figure 5.23 are explained in detailed.

- As similar to first case study building, it has been found that using the heat recovery unit in air handling units does not affect the energy performance of this second case study building and this measure is not included in the single measures shown in Figure 5.23.
- In this thesis research, it has been found that the use of the economizer is not an effect on the energy efficiency of second case study building due to similar reasons of first case study building.

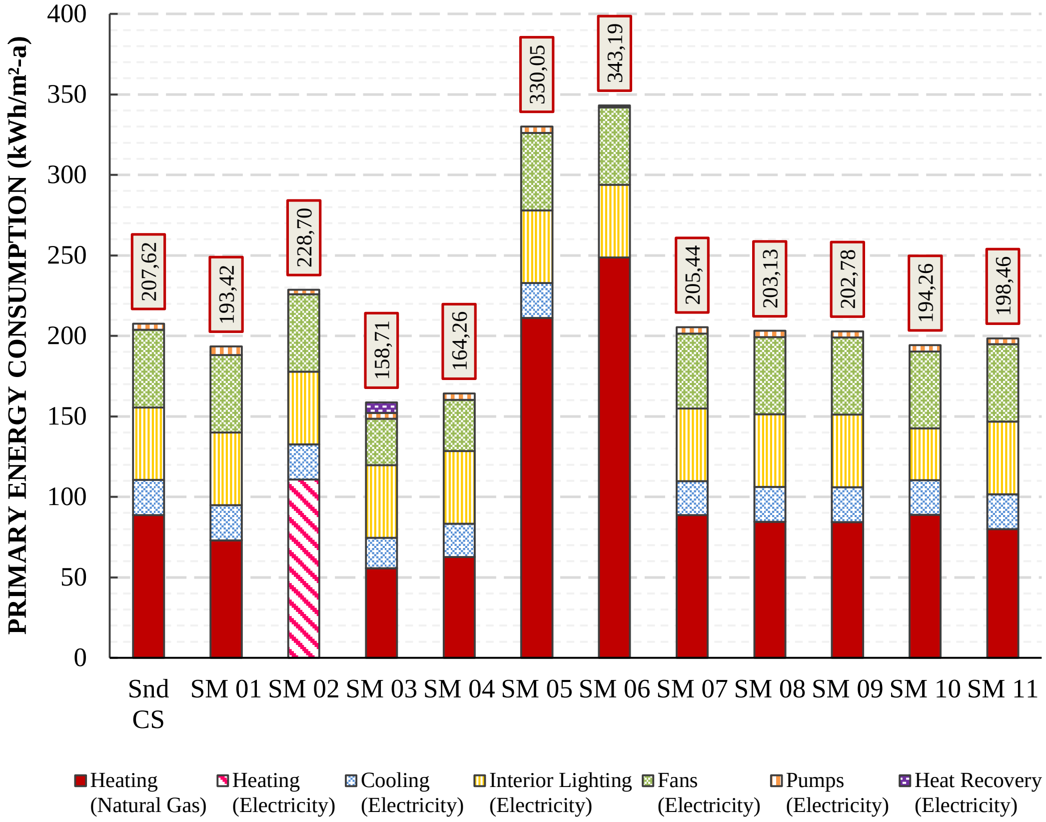

Figure 5.23 : The annual primary energy consumption calculated by dividing into consumption groups of second case study building (Snd CS) and the single measures applied to the second case study building (SM).

Table 5.26 : The applied single measures to second case study building.

Single Measures	Description
Snd CS	Second Case study building
SM01	Radiant heating system
SM02	Ground source heat pump

Table 5.26 (continued) : The applied single measures to second case study building.

Single Measures	Description
SM03	Heat recovery ventilator
SM04	Mechanical ventilation system dependent on occupant density
SM05	Cogeneration system
SM06	Trigeneration system
SM07	Hybrid ventilation
SM08	Solar assisted sanitary hot water production system
SM09	Solar assisted building heating system
SM10	PV system
SM11	Utilizing exhaust gas thermal energy of existing cogeneration system

- The effect of the radiant heating system on the energy efficiency of the building was analyzed in second case study building. When compared with the second case study building results, annual heating consumption improved by 15.76 kWh/m^2.a. However, the annual heating energy saving is less than first case study building result as 2.05 kWh/m^2.a due to decreasing of the amount of fresh air by half because the heating coils in AHUs consumed less energy to condition the less amount of fresh air.

- The effect of ground source heat pump (GSHP) system on the energy efficiency of the second case study building was tested instead of existing heating and cooling system. It is seen that the annual heating consumption of renovated building by using GSHP system is as higher as 21.96 kWh/m^2.a compared to the second case study building annual heating consumption according Figure 5.23. As similar result that have been found in first case study building, it possible to meet the buildings' heating demand efficiently when the GSHP system should be used with a system that operates at lower operating temperature such as radiant heating system.

- Looking at the test results in Figure 5.23, it is seen that there is an remarkable difference between second case study building and this renovated building when compared their annual heating and fan primary energy consumptions. The fan annual energy reduction is 19.32 kWh/m^2.a by utilizing HRV compared to second case study building. This reduction is 11.78 kWh/m^2.a less than the first case study building renovation because the amount of conditioned fresh air is as much as twice in the first case study building. Furthermore, the decline of annual heating consumption is 32.95 kWh/m^2.a by utilizing exhaust air thermal energy via heat exchanger in HRV without using heating coil. The electricity consumption came up 2.8 kWh/m^2.a of electricity in this retrofit unlike the other renovated building due to heat recovery. However, when looked at the total consumption result, the annual energy improvement is 48.91 kWh/m^2.a so it is understood that the application of HRV achieves a dramatic increasing in the building energy performance.

- Another single measure is that the required fresh air is given to each residence unit depending on occupant density. When the simulation results are analyzed, it is seen that the sum of heating, cooling and fan annual consumption decreased by 43.36 kWh/m^2.a and the annual total primary energy consumption reduced considerably. This retrofit application achieves the second striking energy reduction compared to the application of HRV systems.
- The electricity production of cogeneration and trigeneration system in terms of primary energy is shown in Figure 5.24. Looking at this figure, it is understood that the amount of annual electricity production of these systems is quite higher than annual electricity consumption of both cogeneration and trigenearation system retrofit measures seen in Figure 5.23.

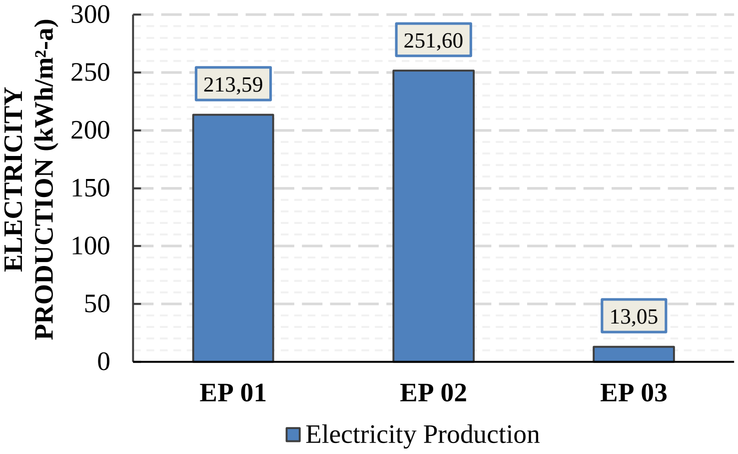

Figure 5.24 : The amount of electricity production in terms of primary energy by using cogeneration system “EP01”, trigeneration system “EP02” and PV system “EP03”.

Due to the similar reason mentioned for first case study building, the usage of cogeneration and trigeneration systems applied for this study is not possible due to prohibitions, restrictions and sanctions in the regulation entitled “Elektrik Piyasasında Lisanssız Elektrik Üretimine İlişkin Yönetmelik”. That’s why, the usage of these CHP systems are not included in the further steps of this research.

- In the second case study building, the natural and mechanical ventilation are used together so the hybrid ventilation is used in this building for getting required fresh air. Looking at the test results, there is a remarkable reduction in the fan annual energy consumption of renovated building. There is also reduction in the annual heating and cooling consumption of this renovated building because the supplied fresh air is conditioned by AHU coils when the windows are closed but the BAS stops the AHU coils when the windows are opened and the interior spaces are naturally ventilated.
- Looking at the test results of sanitary hot water production supported by solar energy system, it is seen that the annual heating consumption decreases by 4.15 kWh/m^2.a. In this building the number of solar collector is similar to the amount of solar collector used in first case study building. When looked at to the first case study building results, the amount of heating energy reduction is approximately similar to second case study building because the demand of sanitary hot water does not change due to constant occupant density in each residence unit. Besides, the number of solar collector in second case study building is similar to first case study application. Thus, the decline of annual heating consumption is also very close between the first and second case study building.
- A system design was made to support both building heating system and sanitary hot water production system assisted by solar energy. In this building the number of solar collector is similar to the amount of solar collector used in first case study building. When the test results were analyzed, it is seen that this retrofit measure ensures lower energy improvement such as 0.35 kWh/m^2.a compared to the measure applied for sanitary hot water production mentioned above. Although the demand of energy was reduced due to the decline of fresh air flow rate, the energy improvement is similar between first and second case study building by using this system due to the plenty of shading effect, the few of sunshine duration and solar radiation intensity. Due

to these reasons, it is understood that the heating consumption has not been saved as much as thought by using solar energy assisted heating system for supporting building heating systems in this single measure application.

- The simulation test results were analyzed the effect of PV systems on building energy efficiency. When these results are analyzed, it is determined that there is a reduction in annual cooling and fan consumption because the PV panels placed in the roof area became like the shading surfaces and declined to the cooling demand of building. Thus, the cooling system in renovated building consumed as less energy as 0.31 kWh/m^2.a. Looking at Figure 5.24, it is seen that the annual electricity generation is 13.05 kWh/m^2.a by using PV systems and in this study, it is assumed that this amount of generated electricity energy is used to support for the electricity demand of fans and pumps in this building. As a result, when the amount of generated electricity and the energy saving in cooling consumption is summed the net annual energy consumption becomes 13.36 kWh/m^2.a in this renovated building.
- It has been determined that the application of the improvement measure by utilizing of the exhaust air thermal energy of existing cogeneration system saves 9.16 kWh/m^2.a of annual natural gas consumption for heating. When looked at the first case study building result, it is seen that, there is a little difference in terms of total energy saving between first and second case study building because the exhaust air thermal energy of existing cogeneration system does not change. However, the more energy was saved in second case study building renovation by 0.81 kWh/m^2.a because the annual heating consumption was reduced due to the decline of fresh air flow rate.

The effects of standard and advanced retrofit measures on second case study building were analyzed above and the reasons and results affected energy improvement were explained in detail. In Figure 5.25, the annual energy consumptions of retrofit packages in terms of primary energy consumption are demonstrated. In Table 5.27, the description of packages (P) seen in Figure 5.26 are explained in detailed.

When the simulation results are analyzed, it is seen that the P01 package saved on considerable energy in annual heating consumption. After the application of the P02 package, an energy consumption reduction was observed in heating similar to P01 but there was a fewer energy saving on annual fan consumption by using hybrid ventilation strategy. With this application, the annual fan consumption decreased by only 1.72 kWh/m^2.a.

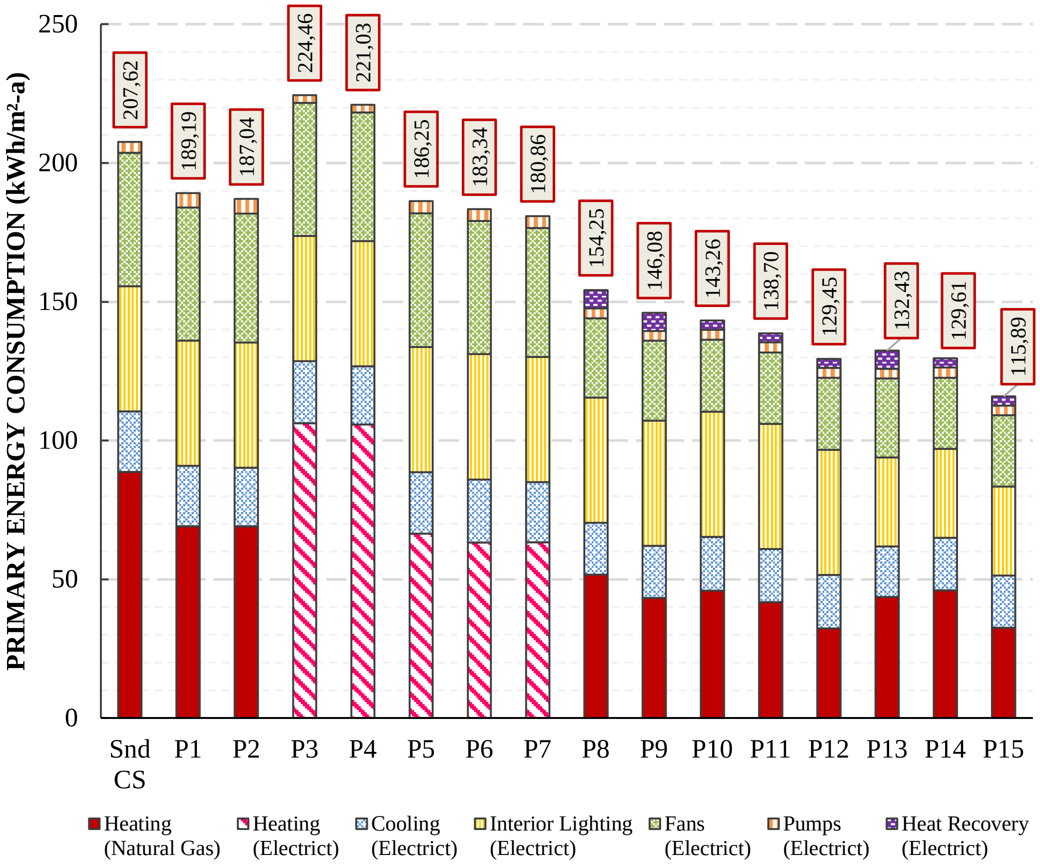

Figure 5.25 : The annual primary energy consumption calculated by dividing into consumption groups of second case study building (Snd CS) and the packages applied to the second case study building (P).

Table 5.27 : The applied packages to second case study building.

Packages	Description
Snd CS	Second Case study building
P01	The utilizing radiant heating system and solar assisted sanitary hot water production system
P02	The utilizing radiant heating system, solar assisted sanitary hot water production system and hybrid ventilation system
P03	The utilizing ground source heat pump and solar assisted sanitary hot water production system
P04	The utilizing ground source heat pump, solar assisted sanitary hot water production system and hybrid ventilation system
P05	The utilizing ground source heat pump and radiant heating system
P06	The utilizing ground source heat pump, radiant heating system and solar assisted sanitary hot water production system
P07	The utilizing ground source heat pump, radiant heating system, solar assisted sanitary hot water production system and hybrid ventilation system
P08	The utilizing heat recovery ventilator and solar assisted sanitary hot water production system

Table 5.27 (continued) : The applied packages to second case study building.

Packages	Description
P09	The utilizing heat recovery ventilator and exhaust gas thermal energy of existing cogeneration system
P10	The utilizing heat recovery ventilator and mechanical ventilation system dependent on occupant density
P11	The utilizing heat recovery ventilator, mechanical ventilation system dependent on occupant density and solar assisted sanitary hot water production system
P12	The utilizing heat recovery ventilator, mechanical ventilation system dependent on occupant density and exhaust gas thermal energy of existing cogeneration system
P13	The utilizing heat recovery ventilator, exhaust gas thermal energy of existing cogeneration system and PV system
P14	The utilizing heat recovery ventilator, mechanical ventilation system dependent on occupant density and PV system
P15	The utilizing heat recovery ventilator, mechanical ventilation system dependent on occupant density, exhaust gas thermal energy of existing cogeneration system and PV system

The reason of this result is that the annual cooling demand of this residential building is not high enough in order to ensure high energy saving by utilizing the hybrid ventilation based on enthalpy control especially in transition seasons of Istanbul climate. Looking at the results of the P03 and P04 packages, it is seen that the ground source heat pump increased the heating consumption although it was used with hybrid ventilation and solar assisted sanitary hot water production system that enhanced the building energy efficiency. Although the annual heating consumption of GSHP in terms of kWh is lower than the annual heating consumption of existing heating system in first case study building, the fact that this system consumed electricity to extract the thermal energy from the earth increases the primary energy consumption in heating. This reason increased the heating energy consumption in packages P03 and P04. Furthermore, in these packages, the GSHP systems were forced to produce hot water at 70°C by extracting the thermal energy from the earth to support the radiator system in first case study building that’s why the energy efficiency of GSHP systems reduced. It is known that the ground source heat pump operates at higher efficiency when used with a system operating at lower operating temperatures, such as a radiant heating system. For this reason the packages P05, P06 and P07 were created. Looking at the results of these packages, it is understood that the radiant heating system operating at 50/30°C improves the energy efficiency of GSHP system and these packages reduced the annual primary energy consumption between 21 and 27 kWh/m^2.a in heating. However, it should be decided whether the GSHP systems are feasible for this retrofit packages after considering the required drilling, labor and system maintenance costs of the boreholes to be opened for this residential building. When the results of the packages in which the fresh air required for each residence unit was supplied by using heat recovery ventilators instead of the existing air handling units are analyzed, it is seen that the improvements are quite high in annual fan and heating energy consumption between P08 and P15 packages. When the annual primary energy consumptions of these packages are compared to others, it is clear that the annual energy savings on the fan consumption play a major role in reducing the total primary energy consumption of the packages between P08 and P15. When the package P12 is compared to P15, it is understood that the contribution of P15 package to the building's annual energy savings is higher due to generating electricity by using PV system. As a result, the P15 became the most energy efficient package compared to all other single measures and packages by ensuring highest energy improvement for first case study building.

5.11 The Calculation of Global Costs of Second Case Study Building

Although the applied retrofit measures increased the energy efficiency of the building, it is just possible to determine whether the applied systems are feasible for the second case study building after calculating the system costs. Therefore, the global cost of each renovated building must be calculated by using the net present value methodology throughout 30 years economic life determined by EPBD-recast for residential buildings. In the Table 5.28, the global cost of case study building and renovated buildings that were retrofitted by utilizing single measures and packages are demonstrated.

Looking at the table above, it is seen that the radiant heating system, SM01, and the ground source heat pump, SM02, increased the global costs of renovated buildings compared to the global cost of case study building. Although the radiant heating system seems more applicable in terms of maintenance, repair and energy costs than the radiator system, the initial investment cost is much higher than the radiator system. Looking at calculations, it was seen that the initial investment costs of radiator system was 5.16 TL/m^2 and the initial investment costs of radiant heating system was 171.48 TL/m^2. Although the initial investment cost of GSHP is not very expensive, the initial investment cost of drilling process which is essential in order to extract thermal energy from the earth and labor cost are so much expensive. The initial investment cost of drilling process is just 181.70 TL/m^2. In addition, the GSHP system uses electricity instead of natural gas for heating of the building which significantly increases the energy costs of the system. According to table, the heat recovery ventilator, SM03, and the mechanical ventilation system dependent on occupant density, SM04, reduce the global costs.

Table 5.28 : The global cost of second case study building and renovated buildings.

Retrofit Measures	Global Costs (TL/m^2)
Second CS	477.54
SM01	703.88
SM02	785.61
SM03	449.88
SM04	399.44
SM07	527.18
SM08	484.01
SM09	504.74
SM10	472.41
SM11	476.84
P01	710.59
P02	759.71
P03	763.84
P04	823.60
P05	914.46
P06	921.29
P07	969.67
P08	456.38
P09	443.45
P10	422.36
P11	428.72
P12	414.58
P13	437.95
P14	416.58
P15	408.92

Both the maintenance cost and the initial investment cost of these systems are very low during 30 years and these systems reduced the energy costs in the life cycle substantially considering the annual primary energy consumption. Looking at the global cost of hybrid ventilation system, SM07, the summation of initial investment cost of window actuator mechanisms and the building automation system are 40.17 TL/m^2 but this system is inadequate to reduce the energy costs because the cooling demand of case study building is not high enough in the warm - humid climate zone. When the global cost of solar assisted systems are analyzed, SM08 and SM09 is not as sufficient as to reduce the heating energy costs due to the low production of sanitary hot water based on occupant density in residential building types. Besides, these systems used to support the existing heating system of case study building operate at low efficiency due to lack of solar radiation and less sunshine duration in the climate zone in which the case study building is located. While the heating cost of the case study building is 137.22 TL/m^2, the heating costs of SM08 and SM09 are 130.79 TL/m^2 and 130.48 TL/m^2 respectively. The initial investment cost of the PV system used in SM10 is 22.55 TL/m^2. When it is assumed that the generated electricity by using PV systems is used to support the energy demands of fans and pumps in the building, the annual electricity saving on the consumption of these systems is 29.15 TL/m^2. In addition, the cooling cost was reduced by 0.24 TL/m^2 due to the shading effect since the PV panels were used in the entire area of roof. When the global cost of the system that supports the existing heating system of case study building by utilizing the exhaust gas thermal energy of existing cogeneration system is analyzed, SM11, the summation of initial investment cost of heat exchanger, accumulation tank and circulation pumps that required for designing this system is 32.56 TL/m^2. This system achieved to reduce both the annual heating energy cost by 13.66 TL/m^2 and the annual electricity consumption by the fans and pumps by 0.68 TL/m^2. However, maintenance and repair of the accumulation tank and circulation pumps added additional cost to the system. Especially, the high capacity of the selected accumulation tank increased the initial investment cost of the system. For this reason, the global cost of the renovated building in which this system is used is higher 0.7 TL/m^2 more than the global cost of the existing building.

5.12 Identification of Cost-Optimum Energy Efficiency Level of Second Case Study Building

Annual primary energy consumptions and global costs of all renovated buildings that are retrofitted by applying retrofit measures are compared simultaneously to determine the cost-optimum efficiency level. This comparison is showed at figure below. Accordingly, the measure that optimizes the second case study building by optimizing it in terms of energy and costs will determine the cost-optimum energy efficiency level of the building. When looked at the Figure 5.26, the red dashed line intersects with Snd CS that represents the annual primary energy consumption and global cost during economic life cycle of the second case study building.

The retrofit measures over this line increase the global cost despite reducing the annual energy consumption of the building. Accordingly, the single measures and packages represents the ground source heat pump and radiant heating system increases the building energy efficiency but these systems also raise the global costs due to fact that the initial investment costs of these systems are still high in Turkey. In particular, P05, P06 and P07 are the improvement packages which the radiant heating system is supported by the ground source heat pump system.

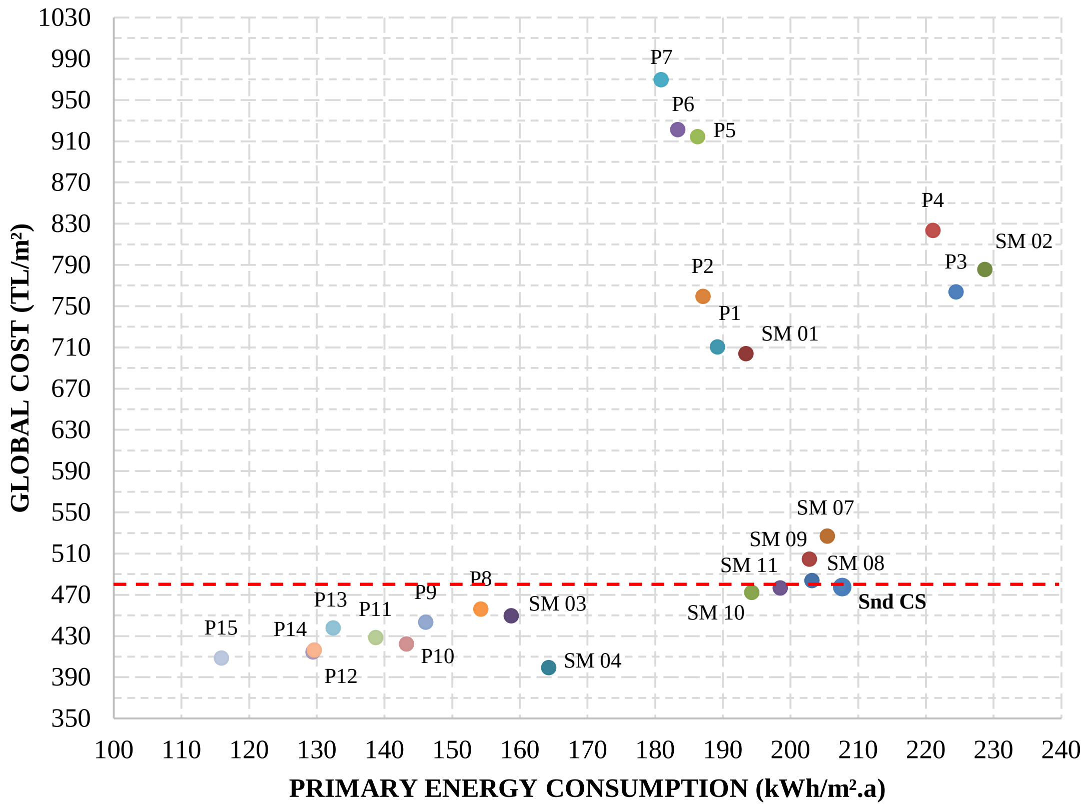

Figure 5.26 : The comparison between global costs and annual primary consumptions of the second case study building and renovated building.

Even though the using of GSHP with radiant heating system that operates at low operating temperature reduces the energy costs considerably, the initial investment cost of both systems increase the global costs of these retrofit packages extremely. The global cost and energy consumption of SM07, SM08 and SM09 which represents the hybrid ventilation, solar assisted sanitary hot water production and solar assisted building heating which their initial investment costs are less was also compared. These measures raise the global cost although they reduce the annual energy consumption of renovated buildings owing to the less cooling demand of this residential building and the warm - humid climate zone where the case study building is located. For supporting the existing heating system, the utilizing of exhaust gas thermal energy of existing cogeneration system, SM11, increased the global cost of the building just 2.09 TL/m^2 during the life cycle. However, in the applications that higher exhaust gas thermal energy, the global cost difference between the second case study building and this renovated building may decreases, moreover the global cost of this renovated building may become fewer than the case study building's. Looking at the results of SM10 that represents the electricity generation by PV systems, it is seen understood that this system reduced the global cost of the building by 5.1 TL/m^2 and it improves the annual primary energy consumption by 13.43 kWh/m^2.a. If the installations of PV system were promoted for the less initial investment cost by publishing new energy regulations by government in Turkey, it would be possible more electricity generation and less global cost by using these systems.

When the retrofit measures under the red dashed line are analyzed, it is seen that SM03 and SM04 reduce the global costs crucially by ensuring high amount of energy saving without compromising the thermal comfort of occupants. The reason of this, SM03 and SM04 measures that reduced the annual energy consumption of the building remarkably decreased the global cost by minimizing the energy costs during economic life-cycle. Looking at Figure 5.26, it is seen that each packages that consist of these single measures reduces both the global cost and the annual primary energy consumption of renovated building significantly. However, the most crucial reduction was obtained by applying P15 package. In this package, SM11 that represents utilizing exhaust gas thermal energy of existing cogeneration system was also combined with other single measure mentioned above. After the applying of SM11 to second case study building, it was established that this system raised the global cost slightly but when this single measure were used with SM03 and SM04 measures, the annual heating energy reduces significantly since there is no need to use heating energy in order to condition required fresh air by using heat recovery ventilator. Therefore, the contribution of the exhaust gas thermal energy to the annual heating consumption of the building increased. This result caused to reduce the global cost of the system by more decreasing the energy cost consumed for heating during the long-term.

When looked at the Figure 5.26, P12 package also includes SM03, SM04 and SM11 single measures that improve both primary energy consumption and global cost remarkably. Similarly P14 package is very close to P12 in terms of both primary energy consumption and global cost. In P14 package, the application of PV system was included instead of the utilizing exhaust gas thermal energy of existing cogeneration system. It was seen that all these single measures that utilized the heat recovery ventilator, mechanical ventilation system dependent on occupant density, exhaust gas thermal energy of existing cogeneration system and PV system developed the building energy performance in respect to energy and cost dramatically during the second case study buildings' economic life. Therefore, it has been decided to create a package in which these single measures are used together for second case study building similar to first case study building. Consequently, P15 is the most energy efficient retrofit package for the second case study building that represents the luxury high-rise residential building type in Turkey. Moreover, this package is cost-optimum retrofit measure for the second case study building in this research.

5.13 Sensitivity Analyzes for Second Case Study Buildings

Similar to sensitivity analyzes of first case study building, the global cost calculations in the first phase considered the average rates of previous years and assumed the discount rate (R_d) as 5.78% for the sensitivity analyzes of second case study building. Then, the discount rate has been reduced as 3% considering the requirements of EU regulation. Fallowed by, this rate has been changed as 9% in the next analyses. Finally, the results were compared in order to observe how the specified measures are affected by the variation of discount rate.

Looking at the Figure 5.27, the sensitivity analyzes' results of second case study building are very similar to first case study buildings in Figure 5.22. As the discount rate decreases, the global costs of single measures and packages are getting away from each other but as the discount rate increases, it is seen that the global costs of these energy improvement measures approach each other. The single measures that labeled as SM07, SM08, SM09, SM10, SM11 (hybrid ventilation, solar assisted sanitary hot water production system, solar assisted building heating system, PV system, utilizing exhaust gas thermal energy of existing cogeneration system respectively) are analyzed and the results compared with each other in terms of impact to cost-optimum level of second case study building. Accordingly, the packages P13, P14 and P15, including the PV system, were also included in the sensitivity analyzes.

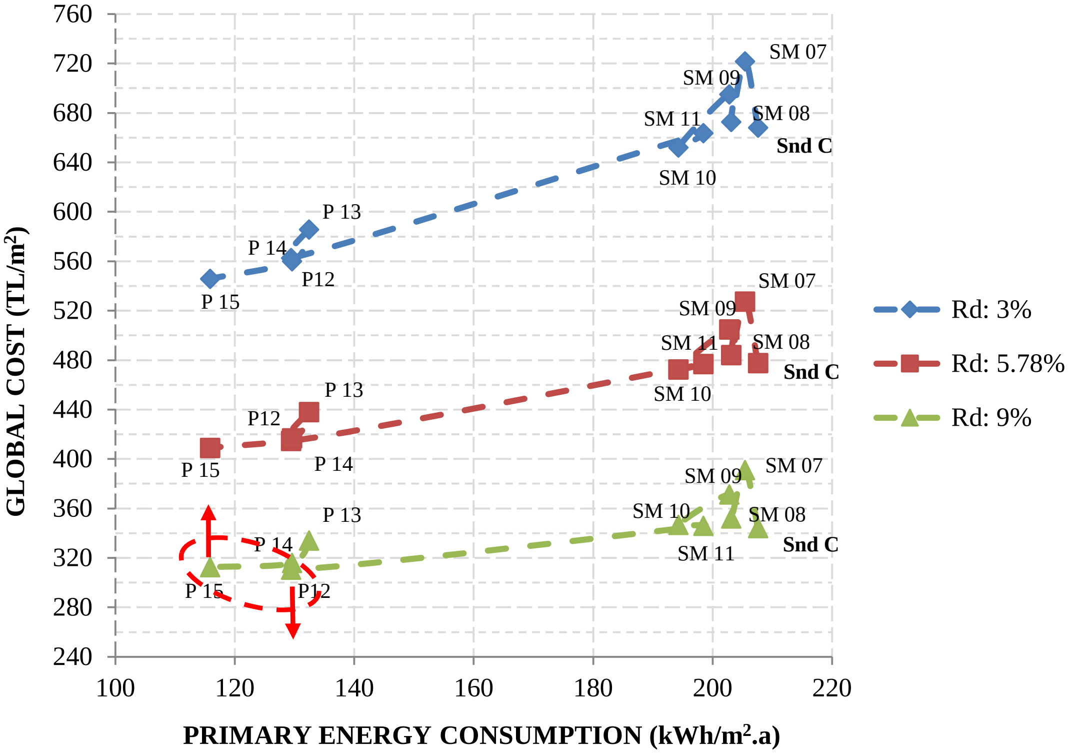

Figure 5.27 : The variation of global costs of measures applied to the second case study building.

The results of the sensitivity analyzes of the measures applied to the second case study building are shown in the graphic above. Looking at the blue dashed line that represents to discount rate of 3%, it is seen that the discount rate of 3% has not reduced the global cost of SM07, SM08 and SM09 below the global cost of first case study building. Besides, the difference of global costs between single measures and second case study has increased generally. These differences are 4 TL/m^2, 10.83 TL/m^2 and 3.70 TL/m^2 for SM07, SM10 and SM11 respectively. When looked at the green dashed line that represents to discount rate of 9%, the global cost of first case study building seems to be still higher than these retrofit measures but the global costs of single measures are closer to second case study buildings'. In this scenario, the global cost difference has decreased to 2.91 TL/m^2, 0.03 TL/m^2, 2.76 TL/m^2, and 2.45 TL/m^2 for SM 07, SM 09, SM 10 and SM 11 respectively.

When looked at the packages, in the scenario which represents the discount rate of 3%, the global cost difference between second case study building and P15 has raised by 53.59 TL/m^2. This global cost difference is 68.62 TL/m^2 in the scenario which is the discount rate of 5.78%. Similar to sensitivity analyzes of first case study building, P15 is the cost-optimum energy efficient measure of second case study building in both these scenarios. However, it is seen that the cost-optimum energy efficiency level changed with a slight difference when the discount rate has been raised to 9%. When the global cost difference between P15 and second case study building is 31.8 TL/m^2, this difference is 33.78 TL/m^2 between P12 and second case study building. Similar to sensitivity analyzes of first case study building, the using of PV systems has enhanced the global cost of P15 when the discount rate has been raised to 9% in second case study building. The keeping constant of energy, running and maintenance costs of this system cause to increase the global costs during the long term and P12 becomes a cost-optimum energy efficient measure when the discount rate is 9% in this analyze.

6. DISCUSSION

According to the results, P15 package (the utilizing heat recovery ventilator, mechanical ventilation system dependent on occupant density, exhaust gas thermal energy of existing cogeneration system and PV system) developed for each case study building is cost-optimum. However, when look at Figure 5.21, the annual primary energy consumption of P15 package is 13.69 kWh/m^2.a lower than P12 and it was found that the global cost of P15 is 5.91 TL/m^2 lower than P12. Similarly, in Figure 5.26, the annual primary energy consumption of P15 package is 13.56 kWh/m^2.a lower than P12 and the global cost of P15 package is 5.66 TL/m^2 lower than P12 when looked at the retrofit applications of second case study building. In this study, PV system was included to P15 as different from P12. This system has reduced both annual energy consumption and the global cost of the first and second case study building. From Figure 6.1, it can be seen that the cost of installation of the PV system from 1998 to 2013 has changed.

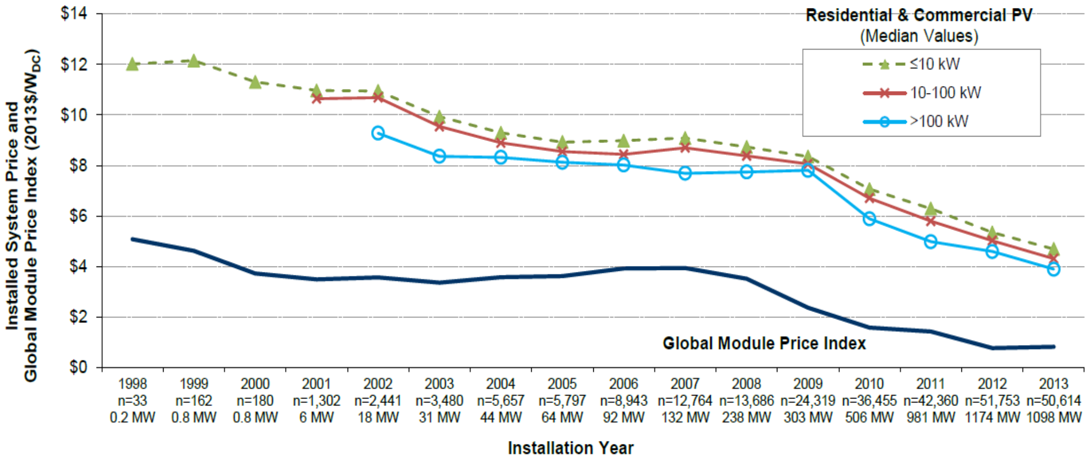

Figure 6.1 : The reduction of PV system prices according to years [87].

This graph shows that prices of the PV system are noticeably decreasing almost every year. According to this result, if the incentives for renewable energy are increased by Turkish government in future and PV systems more cost-effective so the global cost of P15 package may reduce more in the future. Therefore, the investments on the application of PV systems may be enhanced more by contractors and construction project firms and the generation of PV modules may be more possible in terms of costs in further years.

However, the energy efficiency of many renewable energy systems assisted by solar energy is decreasing due to the high shading effect when it is considered that this residential building is located in Levent in Istanbul and many high-rise buildings or the buildings higher than this building are located surrounding of this case study building. Looking at Figure 6.2, it is known that the Özdilek Park building, which was built after the Kanyon building, is very close to Kanyon residential blocks and cause the shading effect on these residential blocks.

Figure 6.2 : The general view of the high-rise buildings surrounding Kanyon building.

Therefore, before the construction of Özdilek Park, it is possible to install PV systems on the roof area of A Block but this system may not be feasible after this construction because the efficiency of the system reduces due to high shading effect. In addition, if there is an investment made for the PV system in the residential blocks before construction, both the investment cost of the system and the energy efficiency of the building will be reduced. Thus, it is clear that the construction laws should be revised as soon as possible for the new buildings to be constructed in Turkey that may affect the energy efficiency and energy investments negatively of the constructed buildings which are located surrounding of buildings to be constructed.

Considering the improvement measures developed for the application of ground source heat pumps in this residential block, it was determined that the highest cost during the installation of this system is drilling and labor costs. It is possible to use bored pile application to make these costs more convenient. At the beginning of the construction of the residential building, drilling and labor costs will be eliminated if the heat pump pipes that extracted required thermal energy from the soil are located into the drilling holes to be opened for the bored pile at the foundation of the building. When this method is used, the system's initial investment cost will be reduced greatly and the global cost will decrease dramatically. Considering this decline, it is also possible that the cost optimum level of high-rise luxury residential buildings changes.

This type of residence is similar to commercial buildings when compared to other types of residential buildings because of the higher transparency ratio and being interactions between the buildings with different occupied areas. Especially in these residential building types, there is more cooling consumption due to the higher solar gain due to the completely glazed façade. In this study, although the improved retrofit measures in terms of hybrid ventilation were far from the cost optimum level owing to the low cooling consumption of the case study building, the annual cooling consumption may reduce for the residential buildings which the annual cooling demand is higher by using different hybrid ventilation strategies. As a result, this energy reduction will decrease the global costs by reducing the energy costs.

7. CONCLUSION

The purpose of this new approach is improving the cost optimum energy efficiency level of luxury high-rise residential buildings in Turkey by supporting the HVAC systems of these buildings using renewable energy systems and lost thermal energies of buildings in the vicinity. In previous literature researches, it was observed that the lost thermal energies of HVAC systems, which is used to conditioned the buildings in the vicinity of this kind of residential buildings, is not used for improving cost optimum energy efficiency level of luxury high-rise residential buildings in Turkey. In particular, it is thought that the thermal energy of the exhaust gases of the heating systems which are ignored at low temperature (100°C and above) will contribute to reducing the primary heating energy consumption of these residential buildings by using air to water heat exchangers. For this reason, the advanced retrofit measures have been improved for the use of the lost thermal energies of HVAC systems of the surrounding buildings in order to increase the cost optimum energy efficiency level of luxury high-rise residential buildings in this Ph.D thesis research. Developed and applied to the building with building energy simulation tools, these measures separated this Ph.D thesis from other previous studies and determined its prerequisite. These advanced retrofit measures that were applied to the existing building by using building energy simulation tools differentiate this Ph.D thesis research from previous studies and determine the unique idea and novelty of this thesis. After the applying of these advanced measure, it has been observed that this retrofit measure applied to an existing building can be partially improved the energy efficiency. If this retrofit measure is developed and applied by using of the building energy simulation analysis from the early design phase of the building, it will be less costly. Furthermore, if the lost thermal energies that are collected not only from the residential building’s own structure but also from the other structures around it are included in the studies of improving the energy efficiency level and if these advanced measures are supported by renewable energy systems that are placed larger sunlighted areas, the building will be closer to the level of nZEB.

Accordingly, when the results of the first and second case study buildings are analyzed, it is seen that although the annual primary energy consumptions of the packages including the heat recovery ventilation system and the mechanical ventilation system dependent on occupant density are different, the global costs of these packages are very close to each other in both case study buildings. It is understood that the differences between global costs are further reduced, especially when the measures that are PV systems and exhaust gas thermal energy of existing cogeneration system are added. First of all, it is understood that the usage of the AHU system for mechanical ventilation in the luxury high-rise residential building types where natural ventilation is not possible is very costly. The use of a heat recovery ventilation systems instead of AHU systems in this type of buildings ensure both supplying fresh air to each residence unit in desired quantity and consuming less energy by operating low powered fans in this same mechanical ventilation process. In addition, there is no need to use heating and cooling coils in this system unlike the air handling unit, since the heat exchanger in this system conditions the outside air without compromising the thermal comfort of the occupants. For designation of initial investment costs of heat recovery ventilation systems in both first and second case study buildings, the guide book of Construction and Installation Unit Prices was used published by Turkish Ministry of Environment and Urbanization. Looking at the list of units in this guide book for selecting a heat recovery ventilation system, it was found that there were no need to select a different systems for different scenarios where 1 ach and 2 ach fresh air were supplied to the residence units because the system group selected for supplying of 1 ach fresh air can also supply 2 ach fresh air to the residence units due to the sufficient of fan power and fan flow rate. For this reason, the all costs without energy costs of the selected heat recovery ventilation system group are the same in both scenarios.

The early design stage is one of the important phase of the building construction in respect to the selection and optimization of HVAC systems. During the early design phase of the building, the building HVAC systems are determined which optimizes low energy consumptions, costs and high user thermal comfort. The optimization studies by using building energy performance tools are more effective during the early design phases when the final decisions are not definite. In this thesis research, the radiant heating system and ground source heat pump was also applied as a measure to the case study buildings. Although these systems achieve to reduce to annual primary energy of the building, the application of these systems are not feasible due to high global costs. If these systems were analyzed by modeling of building energy performance in the beginning of design stage, the global costs of these systems would be less. Especially the drilling and labor costs would be eliminated if the pipes of ground source heat pump are located into the drilling holes to be opened for the bored pile at the construction stage of the building. Therefore, the usage of both these systems together would increase the energy performance of the building and decrease the global cost of the building. However, these systems cause to become higher costs to the tenants and owners if these systems are applied after the construction because the demolition and dismantling costs are included with initial investment costs of these systems. Moreover, these kind of systems, which increase the energy performance of the building and which become low cost systems if they are implemented at the beginning of design stage, should be encouraged by the government, the discount rates of these systems should be lower than those of other systems and the use of such systems should still be mandatory by the relevant ministries in this kind of residential building types.

In this section, information will be given about how citations, quotings and footnotes should be.

7.1 Further Studies

In this research, only A block of an existing residential block group was included in this thesis study and all advanced measure developed for the identification of cost optimum energy efficiency level of building were only applied to A block. In further studies, the energy model should be reanalyzed for this existing residential block by including all other residential block groups to the building energy model and these advanced measures should be reanalyzed to determine how the building energy performance and global costs are changing by applying the these advanced measures to the entire residential block group. In addition, the energy improvement measures that are the application of heat recovery ventilation system, the mechanical ventilation system dependent on occupant density and the exhaust gas thermal energy of existing cogeneration system are the advanced measures that may be implemented to luxury high-rise residential buildings regardless of climate region. In the next study, if the U-values of façade system of the building were revised according to TS 825 and the capacities of the HVAC systems are resized according to climate region, these advanced measures should be reanalyzed to determine how the buildings' annual primary energy consumption and global cost will change.

In addition to this, it is seen clearly by this thesis study that the utilizing of lost heat is an effective measure for increasing the energy performance of the HVAC systems that condition the building and consequently the lost heat is converted into a free energy source, which reduces both annual primary energy consumption and the annual energy costs of the building. However, the exhaust gas thermal energy used as a free energy source is provided by existing cogeneration system operating for the case study building. This system is a microcogeneration system that has very low thermal capacity so it is used only producing sanitary hot water to the case study building. For this reason, the amount of exhaust gas thermal energy provided by this system is also very low. The regulation that entitled "Elektrik Piyasasında Lisanssız Elektrik Üretimine İlişkin Yönetmelik" published by Turkish Ministry of Energy and Natural Resources should be revised for the luxury high-rise residential buildings due to higher energy consumption compared to the other residential building types. Therefore, both the sanitary hot water and the heating demand would be met by choosing cogeneration systems at higher capacities. Moreover, by increasing the amount of electricity generation provided by these systems, the annual electricity consumption of the building would be reduced and the excess produced electricity would be sold to other buildings. As a result, since the system has a larger capacity, the amount of exhaust gas thermal energy will be higher so that the higher thermal energy will further increase the energy performance of the building and reduce the energy costs even more. Furthermore, the trigeneration systems should be designed and operated in these residential building types by revising this regulation. Thus, the exhaust gas thermal energy would be used to meet the cooling demand of the building, so that the CHP system becomes more efficient and the energy performance of the building increases more and the global cost can be reduced even more.

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APPENDICES

APPENDIX A: Global cost calculation sheet.

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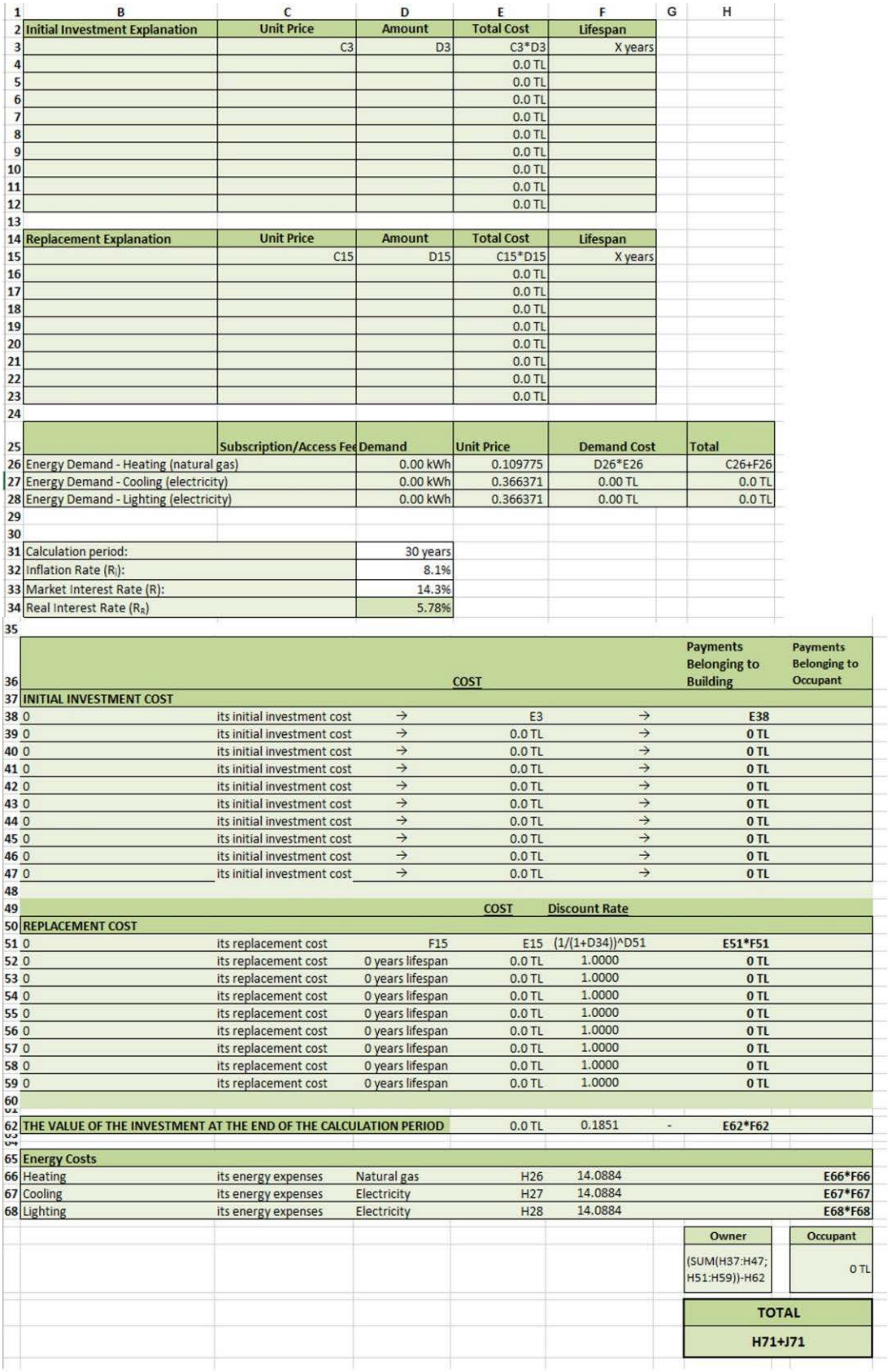

1	B	C	D	E	F	G	H	
2	Initial Investment Explanation	Unit Price	Amount	Total Cost	Lifespan			
3		C3	D3	C3*D3	X years			
4				0.0 TL				
5				0.0 TL				
6				0.0 TL				
7				0.0 TL				
8				0.0 TL				
9				0.0 TL				
10				0.0 TL				
11				0.0 TL				
12				0.0 TL				
13								
14	Replacement Explanation	Unit Price	Amount	Total Cost	Lifespan			
15		C15	D15	C15*D15	X years			
16				0.0 TL				
17				0.0 TL				
18				0.0 TL				
19				0.0 TL				
20				0.0 TL				
21				0.0 TL				
22				0.0 TL				
23				0.0 TL				
24								
25		Subscription/Access Fe	Demand	Unit Price	Demand Cost		Total	
26	Energy Demand - Heating (natural gas)		0.00 kWh	0.109775	D26*E26		C26+F26	
27	Energy Demand - Cooling (electricity)		0.00 kWh	0.366371	0.00 TL		0.0 TL	
28	Energy Demand - Lighting (electricity)		0.00 kWh	0.366371	0.00 TL		0.0 TL	
29								
30								
31	Calculation period:		30 years					
32	Inflation Rate (R_i):		8.1%					
33	Market Interest Rate (R):		14.3%					
34	Real Interest Rate (R_R)		5.78%					
35								
36				COST			Payments Belonging to Building	Payments Belonging to Occupant
37	INITIAL INVESTMENT COST							
38	0	its initial investment cost	→	E3	→		E38	
39	0	its initial investment cost	→	0.0 TL	→		0 TL	
40	0	its initial investment cost	→	0.0 TL	→		0 TL	
41	0	its initial investment cost	→	0.0 TL	→		0 TL	
42	0	its initial investment cost	→	0.0 TL	→		0 TL	
43	0	its initial investment cost	→	0.0 TL	→		0 TL	
44	0	its initial investment cost	→	0.0 TL	→		0 TL	
45	0	its initial investment cost	→	0.0 TL	→		0 TL	
46	0	its initial investment cost	→	0.0 TL	→		0 TL	
47	0	its initial investment cost	→	0.0 TL	→		0 TL	
48								
49				COST	Discount Rate			
50	REPLACEMENT COST							
51	0	its replacement cost	F15	E15	(1/(1+D34))^D51		E51*F51	
52	0	its replacement cost	0 years lifespan	0.0 TL	1.0000		0 TL	
53	0	its replacement cost	0 years lifespan	0.0 TL	1.0000		0 TL	
54	0	its replacement cost	0 years lifespan	0.0 TL	1.0000		0 TL	
55	0	its replacement cost	0 years lifespan	0.0 TL	1.0000		0 TL	
56	0	its replacement cost	0 years lifespan	0.0 TL	1.0000		0 TL	
57	0	its replacement cost	0 years lifespan	0.0 TL	1.0000		0 TL	
58	0	its replacement cost	0 years lifespan	0.0 TL	1.0000		0 TL	
59	0	its replacement cost	0 years lifespan	0.0 TL	1.0000		0 TL	
60								
62	THE VALUE OF THE INVESTMENT AT THE END OF THE CALCULATION PERIOD			0.0 TL	0.1851	-	E62*F62	
65	Energy Costs							
66	Heating	its energy expenses	Natural gas	H26	14.0884			E66*F66
67	Cooling	its energy expenses	Electricity	H27	14.0884			E67*F67
68	Lighting	its energy expenses	Electricity	H28	14.0884			E68*F68
							Owner	Occupant
							(SUM(H37:H47; H51:H59))-H62	0 TL
							TOTAL	
							H71+J71	

Figure A.1 : Global cost calculation sheet of the thesis study [Yılmaz et al. (project team), 2015].

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