Energy and Exergy Efficiency Analyses of High-Performance Buildings

A Dissertation

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Energy and Exergy Efficiency Analyses of High-Performance Buildings

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DEDICATION

To …

My mother and father, may Allah have mercy on them

My brothers and sisters who supported me during this long study journey

My teachers who taught me

My friends who encouraged me

ABSTRACT

Reducing building energy density has become one of the global requirements to a decrease fuel consumption and emission production, and consequently making our world sustainable. The high value of energy consumed by buildings highlights the importance of the requirement to decrease building energy demand. The aim of this thesis is to analyze a well-designed existing building exegetically, exergo-economically and environmentally in order to determine the consequent effects of any options for improvement.

In the first part of the study, the building was analyzed statically and dynamically (hourly) over a year for the heating season to specifically highlight the differences between them in addition to an accuracy estimation. In the second part, actual experimental processes for improvement that were applied to the buildings at different stages were investigated as well. For this study, the SCOLA Building at Ozyegin University Campus in Istanbul is considered. SCOLA was designed to be one of the least amounts of energy consuming buildings in Turkey. It includes 291 rooms with a floor area of 17,250 m^2 and 6 floors. A natural gas boiler that produces hot water is used to heat the building with a distribution network and four fan coils. The hourly operational information about the heating system was recorded and used in tandem with the local weather data. The calculations were applied both in static and dynamic fashion, based on the recommendations from the facility management team. Improved pre-design tools were used to implement these details to the simulations.

The simulations reveal that energy demand for the building can be as low as 1.38 MW and exergy is 1.34 MW at peak load, while their annual values are 8.9 GJ and 8.2 GJ, respectively. Based on the calculations, the specific heating demand at the building is found to be 25 W/m^2 while the annual specific heating demand is 80 W/m^2/yr (if heating is evenly distributed to the year; actual energy density for the building is determined to be 50 W/m^2/year, considering

summer months). The reduction in energy and exergy demand reaches 6% during working hours of the 21st January 2016, simultaneously reducing the cost and the CO_2 emissions. The increase in exergetic cost coefficients reflect the reduction in the exergy efficiency of the heating system components based on the ambient temperature change. It is noted that a dynamic analysis using average monthly temperatures is preferred over a static analysis. However, if a simpler static analysis is to be used, an annual average temperature needs to be identified for a specific climate zone and building type. For Istanbul, an average temperature of 14^{o}C is recommended for a static analysis.

We also examine how different engineering implementation strategies, in addition to the original design, can improve the thermal performance of the building. Five different cases (scenarios) are investigated in addition to the original case which is considered to be the base case (1st case). The second is the use of a ground air heat exchanger, whereas the use of better insulation materials and the use of glass and roofs is the third case study representing the traditional approach. The use of solar PV-panels over the entire building constitute the fourth case, and the integration of a campus tri-generation system to the building energy modalities is considered as the fifth case. Applying all these processes to the building simultaneously is considered as the sixth scenario. All these changes have already been implemented in the building where the real time data are being collected. Performance simulations based on exergy, exergoeconomic, and environmental analyses are conducted and presented. Energy and exergy flow diagrams from all sources to the envelope for all cases are also outlined and conclusions are drawn.

A Marginal Abatement Cost Curve (MACC) was constructed based on exergy analysis in order to achieve more accurate results. MACC analysis outlines the cost and carbon dioxide emission savings simultaneously. Its results help policymakers to employ the best potential option.

ÖZETÇE

Dünyanın daha yaşanabilir ve sürdürülebilir olması için alınan ana tedbirler arasında, dünyadaki enerji tüketiminin kısıtlanması yoluyla sera gazlarının salınımının önüne geçilmesi öncelik kazanmıştır. Binalarda yüksek miktarda kullanılan enerji tüketimi, enerji ihtiyacımızın önemli bir kısmını oluşturur. Bu tezin amacı, varolan binaların çok daha iyi biçimde tasarlanmasi, ve bunun sonucunda çevresel ve sosyo-ekonomik analizini değerlendirerek iyileştirme seçeneklerini saptamaktır. Çalışmanın ilk kısmında, binalar sadece ısıtma mevsiminde statik ve dinamik (saatlik aralıklarla) olarak yıl boyunca analiz edilmiş olup, iki yaklaşımın arasındaki farklar belirlenmiştir. İkinci kısmda ise, binalara farklı kısımlarda uygulanan gerçek deneyimsel iyileştirme süreçlerinin etkileri irdelenmiştir.

Bu çalışmada Özyeğin Üniversitesi Kampusunda bulunan SCOLA binasi çalışılmıştır. Bu bina, Türkiye'deki en az enerji tüketen binalarından birisi olarak tasarlanmıştır. Binanın 291 odası olup, 6 kat ve 17.250 m^2 dir. Binadaki ısıtma sistemi, doğal gaz kazanıyla sıcak su elde edilip, binayı dört-boru fan sistemiyle ısı dağıtılır. Bütün ısı sistemi bilgileri, iklim verileriyle birlikte toplanmıştır. Hesaplamalar, ileri tavsiyelere uygun olarak statik ve dinamik olarak yapılmıştır.

Bu hesaplamalar sonucu, bina averaj enerji talebi 1.38 MW ve ekserji 1.34 MW olarak tespit edilmiştir. Bunların yıllık değerleri ise sırasıyla 8.9 GJ ve 8.2 GJ olarak hesaplanmıştır. Spesifik enerji yoğunluğu 25 W/m^2 olarak, ve de yıllık ısı talebi de 80 W/m^2/sene olarak bulunmuştur. (Bu değer, ısıtma sezonu baz alınarak averaj bulunduğu zaman çıkan değerdir. Bina enerji yoğunluğu, yaz aylarını da dahil ederek 50 W/m^2/sene olarak ölçülmüştür.) 21 Ocak 2016 tarihi itibariyle çalışma saatlerinde enerji ve ekserji taleplerinde %6 bir düşüş kaydedilmiştir. Bu değerler, eş zamanlı olarak hem emisyon ve hemde maliyet için geçerlidir.

Ortam sıcaklık değişimi sayesinde tefsir maliyet katsayısının artması, isitma sisteminin temel unsurlarının veriminde düşüş sağlanmıştır. Statik analiz yerine, aylık ortalama sıcaklık değerleri kullanılarak dinamik analiz tercih edilmiştir. Eğer basit bir statik analizi yapılacaksa, belli bir iklim kuşağı için yıllık sıcaklık ortalaması ve bina tipi belirlenmelidir. Istanbul için ortalama 14^{o}C en uygun referans sicaklik olacak belirlenmistir.

Binanın orjinal durumuna ilave olarak, farklı mühendislik stratejilerinin uygulanması, binanın termal performansını iyileştirmesi beklenmektedir. Baz olarak alınan orjinal duruma ilaveten, beş ayrı senaryo daha incelenmişdir. Bu senaryolar arasında, zemin hava ısı değiştiricisi (ground based heat pump) birinci senaryodur. Daha iyi ısı yalıtım malzemeleri, camlar ve çatıların bir kullanılması geneleksel bir çalışmadır, ve ikinci senaryo olarak düşünülmüştür. Dördüncü senaryo tüm bina üzerine solar PV-panellerinin kullanımıdır. Beşinci senaryo bina enerji yöntemlerine tri-generasyon sistemi dahil edilmesidir. Altıncı senaryo, tüm bu sistemlerin aynı anda binaya uygulama şeklidir. Binaya tüm bu değişimler hali hazırda uygulanmış olup, gerçek zamanlı veriler toplanmıştır. Performans simülasyonlari ekserji, ekserji ekonomisi ve çevre analizlerine bağlı olarak yapılmıştır. Bütün kaynaklardan enerji ve ekserji akış diyagramları tüm senaryoları kapsıyacak şekilde Marjinal Maliyet Indirim eğrisi (MACC) çizilip, CO_2 emisyon minimizasyon grafiği gösterilmiştir ve uygulanan bu stratejilerin çevresel ve finansal etkileri vurgulanmıştır. Bu çalışmaların karşılaştırmalı sonuçları da listelenmiştir.

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NOMENCLATURE

Nomenclature	Describtion	Unit
A	Area	m^2
AST	Apparent time in decimal hours	minute
BNI	Beam normal irradiance	W/m^2
C	Exergy cost coefficient	USD/GJ
Cl	Clearness number.	-
COP	Coefficient of performance	-
DHI	Diffusion horizontal irradiance	W/m^2
E	Energy	W
ED	Total energy demand	W
ET	Equation of time	-
F	Factor	-
G	Transmittance	-
GR	Ground reflectance	-
GRC	Ground-reflected component	W/m^2
h	Enthalpy	kJ/kg
hc	Heat transfer coefficient	W/m^2
I	solar flux	W/m^2
i	Interest factor	-
IN	Normal direct irradiation	W/m^2
LL	Local latitude	Degree
LON	Longitude of site.	=
LSM	Longitude of local standard time meridian.	=
LST longitude	Local standard time	hours
m	Mass flowrate	kg/sec
No	Number	-
nd	Days number	-
nr	Air exchange rate	h^{-1}
P	Electrical energy	W

Nomenclature	Describtion	Unit
Q	Heat (losses or gain)	W
R	Reduction	-
S	Entropy	kJ/kg.K
SH	Sun position	hour angle
SI	Sustainability Index	-
T	Temperature	K
TZ	Time zone	hours
U	Overall heat transfer coeff.	$W/m^2.K$
V	Volume	m^3
VHR	Ratio of clear-sky diffuse irradiance on a vertical surface to clear-sky diffuse irradiance on the horizontal	-
Z	İnvestment cost coefficient	USD/h
XF	External shade factor	-
CRF	Capital recovery factor	-
Y	Annular emission of CO_2	ton
IF	İnternal shade factor	-
XD	Total exergy demand	W
AF	Frame fraction [-]	-
Ny	Operating period (year)	year
W	Work	Watt
Greek symbol		
Δ	Difference	-
Φ	Energy	W
η	Efficiency	-
λ	Maintenance factor	-
ρ	Density	Kg/m^3
ψ	Exergy	W
α	Absorptance of surface for solar radiation	-
ε	Hemispherical emittance of surface	-
Γ	Solar time Sunday	hours

Nomenclature	**Describtion**	**Unit**
δ	Solar declination	degree
β	Solar altitude	degree
θ	Angle of incidence	degree
γ	Surface-solar azimuth angle	degree
ξ	Solar azimuth	degree

Subscripts		**Unit**
Air	Air	
app.	Appliances	
Aux	Auxilary electricity	
B	Boiler	
Buil.	Building	
CH	Chiller	
Cooling	Cooling load	
CW	Cold water	
D	Demand	
dest	Destruction	
DHW	Domestic hot water	
Dis	Distribution	
e	Energy	
elec.	Electricity	
FC	Fan coil	
flue	Flue gas	
g	Glass windows	
h	Heating demand	
heating	Heating load	
HS	Hot stream	
HW	Hot water	
Hrecov	Ventilation heat recovery system	
i	Light	
in	İnlet	
j	Heating system component	
k	Building component	
light	Light	
Net	Conditioned area	
Nor		

Subscripts		**Unit**
o	Reference	
occ.	Occupancies	
om	Outdoor daily mean temperature	
out	Outlet	
P	Primary energy	
q	Quality (exergy factor)	
R	Room	
s	Solar	
SC-O	Original case	
SC-k	Kth case	
t	Total	
trans	Transmission	
Tri	Tri-generator	
θ-n	Hour ago	
v	Ventilation	
ve	Electricity. for ventilation	
W	Water	
X	Exergy	
comp	Compressor	
cg	Cooling gas	
gen	Generation	
cond	Condenser	
evap	Evaporator	

CHAPTER I

INTRODUCTION

1.1 *Background and Motivation*

We all observe the impact of climate change on our daily life's day by day. It is well known that the high percent of Green House Gas (GHG) is the main reason for this problem which has become a serious problem that causes the trapping of radiative energy in the atmosphere. The main reason for this high percentage of CO_2 in the atmosphere is due to the energy demand that is increasing day by day. Figure 1.1 shows how the energy demand from different sectors will increase until 2040 (BP Energy Economics, 2018). Figure 1.2 summarizes the most negative effects of this increasing energy consumption on our world. The high demand for energy was assumed to be caused by cars, manufacturing, and power plants (Figure 1.3). Yet, recently, the World Business Council for Sustainable Development considered buildings as one of the five users that have the highest energy consumption all over the world (WBCSD, 2009). For example, in the European Union, the demand for energy for building constitutes about 41% of the total energy demand and 36% of CO_2 emissions (Biserni and Garai 2015), and it accounts for more than one third of the world's primary energy demand (Sakulpipatsin *et al* 2010).

The main steps for developing the low energy buildings concepts are strongly encouraged as shown in Fig. 1.4. Most countries are not concerned about increasing the growth of this problem, especially in developing countries even though some countries have started strategies that lead to reducing the percent of CO_2. Europe Union is one of the first that set target for reducing gas emissions by 20% and saving 20% of energy by the year 2020 (Gros and Roth, 2012).

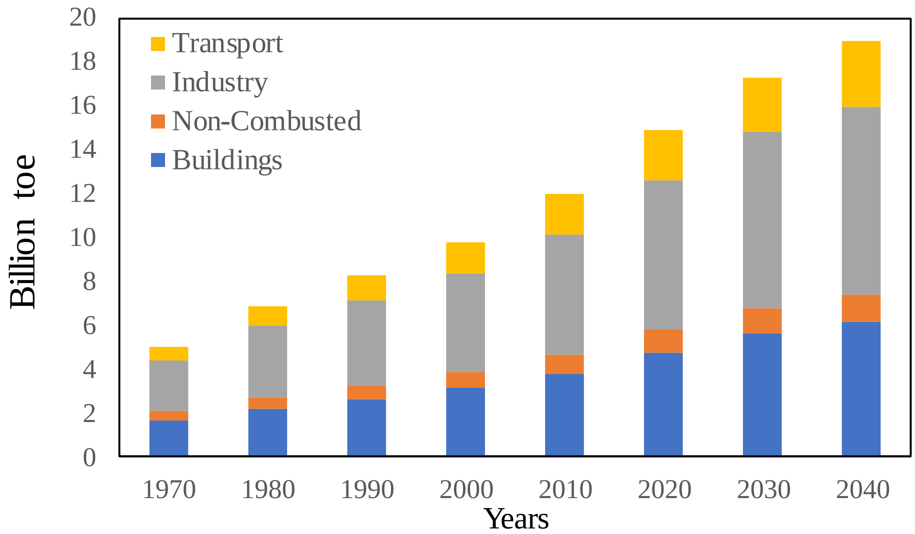


Figure 1. 1 Growing of energy demands around the world (BP Energy Outlook 2018). Toe: The ton of oil equivalent which is a unit of energy defined as the amount of energy released by burning one ton of crude oil. It is sometimes used for large amounts of energy

Figure 1. 2 Negative effect of climate change that occurs due to CO_2 emission.

Figure 1. 3 The first concept the main reason for CO_2 emissions.

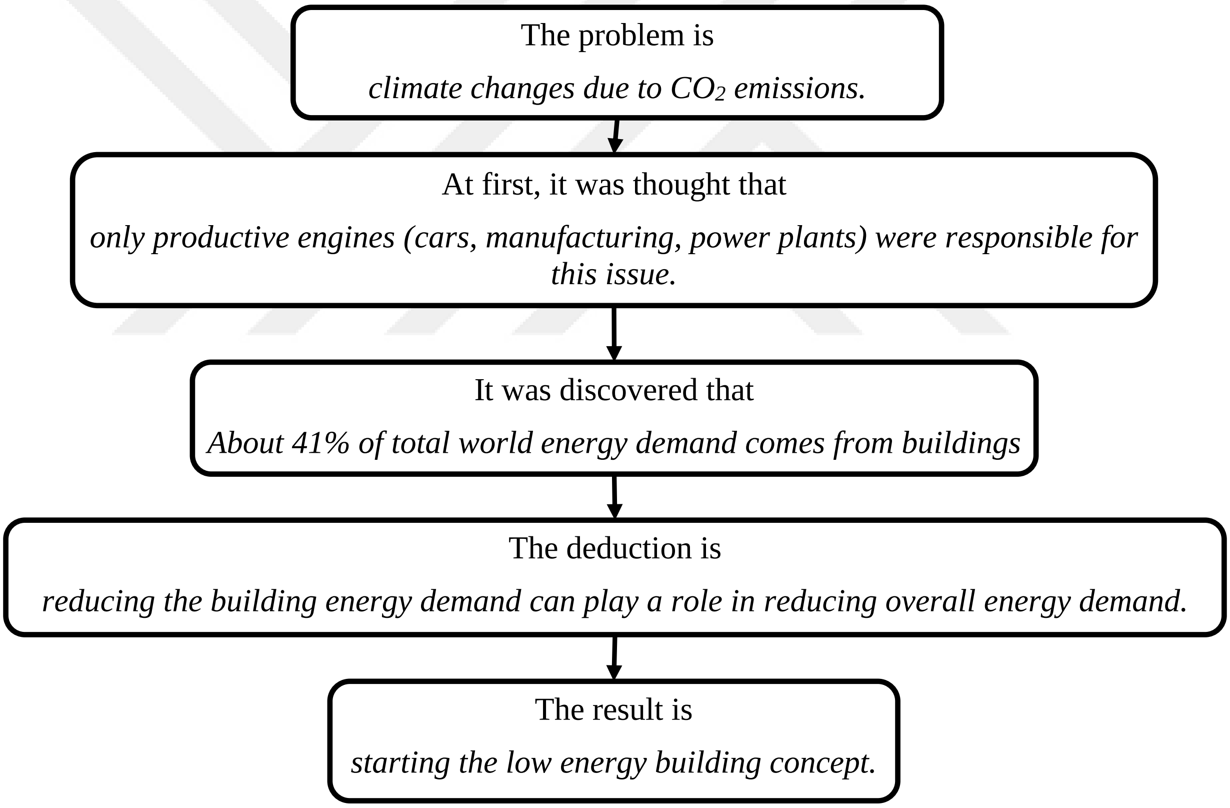


Figure 1. 4 The abstract of the low energy concept.

Based on the Sustainable Building and Construction Initiative of the United Nations Environment Program, buildings can be considered the key for sustainable development (Gonçalves, 2013). All data indicates that effective exploitation of this sector will lead to considerable reduction in CO_2 emission in addition to making the use of energy resources more profitable and efficient. Akshey et al., 2018 defined sustainable buildings as the tool that achieves an efficient use of building resources in the different forms of energy, water, and materials that lead to the reduction of the impact of buildings (Akshey *et al* 2018).

In order to achieve the required reduction in energy demand, researchers have started to analyze buildings in order to reduce energy consumption and, consequently, reduce the demand for power around the world. The targets of improving the efficiency of power productions and using building with good performance need to go hand in hand. These buildings are called low energy buildings because they consume less energy than others buildings; this is mainly achieved by applying certain principles which include using renewables and other flows of free energy, matching the quality levels of supply and demand, optimizing storage strategies, using high quality energy sources, and avoiding any processes that cause exergy loss (Jansen *et al* 2012).

The best way to analyze these buildings is the exergy analysis because it combines both the first law and the second law of thermodynamics although energy analysis is usually performed based on fundamentals of the first law only. In such buildings, there are many ways for energy to flow in and out, including the electricity of lamp light, thermal energy due to transmitted solar energy, the electricity of cooling and heating systems, and energy consumed due to ventilation. Therefore, it is necessary to study the whole system, which includes all of these subcomponents (Mahlia *et al* 2011).

NEED4B, which is one of the EU projects carried out by the Center For Energy, Environment and Economy (CEEE) at Ozyegin University in Istanbul, involves key expertise to demonstrate the technical, social and economic feasibility of this challenge (NEED 4B, 2018). The project is coordinated by CIRCE, and Zaragoza, Spain. Altogether, the project involves 14 experienced partners from five different EU countries covering the most relevant stakeholders: six SMEs (contractors/real-state, engineering, ICT and architects), three large industries (contractor/real-state, engineering and wood industry), two research centers, and three universities. This dissertation aims to highlight the economic and environmental effects of low energy buildings and the effects of different alternatives resources and low exergy technology or devices. To make any process or tool applicable. the economic benefit should be considered, especially for investors. Simply put, applicable approaches that make the feasibility of such building easy to see for designers, investors, and users will encourage communities to build such buildings as well as explaining options for high-performance buildings that lead to improvement in their performance. All of the above motivated us to present this study.

1.2 *Statement of the Problem*

In order to investigate the complicated discussion about buildings should be analyzed in depth. Energy analysis is a traditional method which is usually performed based on the fundamentals of the first law of thermodynamics; thus, there are limitations to applying this analysis to building (Schmidt, 2009). However, exergy analysis, which represents a different method combining both the first and the second laws of thermodynamics and providing detailed results that allow significant improvements in building performance (Dincer and Rosen 2000, Mahlia *et al* 2011, Teres-Zubiaga *et al* 2013). On the other hand, enhancements based on energy and exergy analyses would not be sufficient without detailed economic and environmental studies. It is desirable, in determining the energy cost and the feasibility of any processes for improvement, to use an exergoeconomic approach which combines the cost of input energy, capital investment, and exergy values of input and output streams for each component (Lozano and Valero 1993, Açikkalp *et al* 2014, Biserni and Garai 2015). In addition, based on the new policies of many countries such as the EU, China, and India, an environmental analysis related to CO_2 emissions is essential for designing and constructing environmentally friendly high-performance buildings (BP Energy Economics, 2018). It can be concluded from studies mentioned above that, to get accurate, efficient, and sufficient investigations, exergy, exergoeconomic, and environmental analyses should be considered. Even though these analyses can be applied statically in locations where the weather temperature is constant or dynamically in locations where the temperature changes hourly for an entire year, most previous studies claimed that the dynamic analysis is better than the static analysis in determining the performance of a building (Yücer and Hepbasli 2014). However, no study is available that reports the differences between the dynamic and static analyses in a clear and detailed way. Moreover, none of previous studies investigated the opportunity of minimizing the divergence between the static and dynamic analyses. Hence, in present the study, both analyses are considered energetically, exegetically, exergoeconomically, and environmentally.

Moreover, in order to reduce energy consumption in the building sector, many alternative resources and processes for improvement that can be added to the air conditioning system of the buildings were investigated. Good architectural design (walls, roofs, shades, daylighting, and so on), PV panels, ground air heat exchangers, hydraulic power plants, geothermal energy plants, wind turbines, and tri-generation systems can enhance buildings performance. The energy and exergy flow from the source to the building envelope should be determined for all alternative energy resources or processes. The feasibility of all these alternatives need be estimated and detailed in a simple methodology that allows engineers to follow it. This will be another task of this study.

1.3 *Objectives and Research Questions*

The buildings analysis needs to be integrated because of direct and indirect connections with economic and environmental issues. This methodology should be understandable and flexible enough to be applied to other buildings that have different energy resources. In this study, energy and exergy analyses were applied to an existing high-performance building. The advantage of a dynamic analysis relative to a static analysis was explained. The opportunity to minimize the divergence between these two analyses was investigated as well. Exergoeconomic and environmental aspects were considered in this study. An integrated approach for fulfilling these analyses was presented. The architecture effects of such high-performance buildings were studied. The feasibility of improving processes such as architectural effects and new energy resources was estimated. The main cases analyzed ground air heat exchange (GAHX); increasing the insulation of walls, roofs, and window; PV panels; tri-generation systems; and applying all of them simultaneously. Based on the objectives, seven main research questions (RQ) were formulated that this study will try to answer.

RQ.I Is it possible to simplify the exergy, exergoeconomic, and environmental approaches?

RQ.II Are there real differences between static and dynamic analyses and, if so, is there an opportunity to minimize the difference?

RQ.III For high-performance buildings, is there a potential chance to improve their performance? In other words, what is the effect of the architectural aspect on the building's performance?

RQ.IV What is the feasibility of using ground air heat exchangers in buildings?

RQ.V Are there potential gains from an architectural effect?

RQ.VI What is the feasibility of adding solar energy to the performance of the building?

RQ.VII Does the tri-generation system cause an essential reduction in energy demand and consequent economic and environmental impacts?

RQ.VIII Can we consider the exergy, exergoeconomic, and environmental analyses as one integrated method in evaluating a building's performance and the feasibility of using new resources?

1.4 *Thesis Outline*

This thesis is consisted of five chapters: an overview of the subject, a review of the most recent pertinent scientific literature, methods, results and discussion, and the conclusions. This chapter is an introduction to the thesis. Chapter 2 involves most of the definitions and explanations that are mentioned in the following chapters and used in the mathematical model. Previous studies are detailed in Chapter 3. Information about and an explanation of the actual case study is presented in Chapter 4. Mathematical model and the equations that are applied in this study are explained in Chapter 5. Results and Discussion is considered to be the sixth chapter. The last chapter represents the conclusion and recommendations.

CHAPTER II

LITERATURE SEARCH

For decades, researchers have investigated the increase in energy demand that has become a real threat to our life on this planet. At first, some of them focused on improving the productive power of engines, and others tried rationing energy use. Since that date, they have exerted strenuous efforts to achieve their aim. Some of them began with energy analysis which, as they have discovered recently, is insufficient (Torio & Schmidt 2007). Analyses of such complicated problems cannot be done using the conservation of energy principles alone. Instead, both the first and the second laws of thermodynamics need to be considered. This requires combining exergy and energy analyses with the goal of sensible improvements in the performance of building (Dincer & Rosen, 2012). Exergy analysis leads to a better understanding of the influence of thermodynamic phenomena on the effectiveness of the process and the highlighting of the importance of different thermodynamic factors and the most effective ways to improve energy conversion processes (Yucer & Hepbasli, 2013). In addition to energy and exergy reduction, the consequent effect economy and CO_2 emission should be considered in such analyses to get an inclusive concept of energy consumption. Without the inclusion of the exergy concept in the analysis, major consequent problems and solutions remain hidden in the building sector (Gonçalves, 2013). Based on that, for an integrated approach to these kind of investigations, exergoeconomic and environmental analyses should be applied along with exergy analysis.

In this section, large numbers of previous studies on energy, exergy, exergoeconomic, and environmental, analyses were reviewed statically and dynamically. To make this section understandable, it will be divided into six sections organized as follows. Section 2.1 presents main definitions and explains low exergy thought.

2.1 *Main Definitions and Low Exergy Thought*

2.1.1 Thermodynamics

In physics, thermodynamics represents the ability to cause work. In chemistry, it is an attribute of a substance as a consequence of its atomic, molecular; or aggregate structure; and a chemical transformation that is accompanied by a change in one or more of these kinds of structures. There are two main types of energy, kinetic and potential energy (Çengel & Boles, 2011).

2.1.2 Energy

In the Greek language, energy is “therme”; therme represents heat, and dynamic represents power. Put together, thermodynamics is today’s term for the science of energy. Also, today thermodynamics represents all aspects of energy and energy transformation (Çengel & Boles, 2011). Moreover, Jim Lucas on the LiveScience website defined thermodynamics as the branch of physics that deals with the relationships between heat and other forms of energy. In particular, it describes how thermal energy is converted to and from other forms of energy and how it affects matter (Winterbone & Turan, 2015a).

2.1.3 Entropy

Entropy is defined as "a measure of the disorder or randomness in a closed system" that also inexorably increases. All thermodynamic systems generate waste heat. This waste results in an increase in entropy, which for a closed system is "a quantitative measure of the amount of thermal energy not available to do work," according to the American Heritage Dictionary. Entropy in any closed system always increases; it never decreases. Additionally, moving parts produce waste heat due to friction, and radiative heat inevitably leaks from the system (Dincer and Rosen 2012).

2.1.4 First Law of Thermodynamics (FLT)

The first law of thermodynamics is as follows: the value of the net work done by or on a closed system undergoing an adiabatic process between two given states depends solely on the end states and not on the details of the adiabatic process (energy conservation statement), The change in the total energy of a closed system during a process is equal to the heat transfer to the system minus the work done by the system (Çengel & Boles, 2011).

2.1.5 Second Law of Thermodynamic (SLT)

The second law of thermodynamics is as follows: it is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body (Clausius statement). It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of work to its surroundings while receiving energy by heat transfer from a single thermal reservoir (Kelvin-Planck statement). The law also states that heat energy cannot be transferred from a body at a lower temperature to a body at a higher temperature without the addition of energy. This is why it costs money to run an air conditioner (Çengel and Boles 2011).

2.1.6 Exergy

There are variant definitions of exergy, but most of them agreed about availability, which means available work that can be extruded from any system. In thermodynamics, the exergy of a system is the maximum work possible during a process that brings the system into equilibrium with a heat reservoir (dead state) (Dincer & Rosen, 2012). Moreover, exergy is the minimum theoretically useful work required to form a quantity of matter from a substance present in the environment and to bring the matter to a specified state. It is also a measure of the departure of the state of the system from that to the environment and is therefore an attribute of the system and environment together (Bejan 2002). Tsatsaronis (2007) said that the exergy of a thermodynamic system is the maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only (Tsatsaronis, 2007).

In addition to the definitions, there are different classifications of exergy; one of them is presented in Figure 2.1 which classifies exergy in different way (Winterbone and Turan 2015). In order to provide more information or knowledge about the differences between energy and exergy, Table 2.1 provides a comparison,

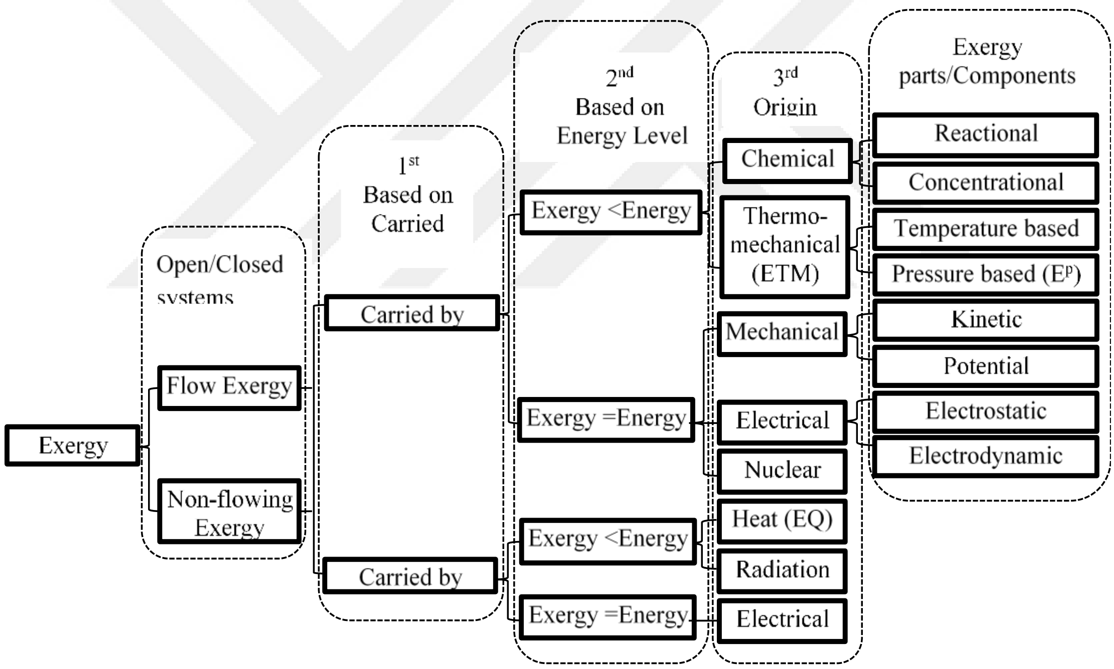


Figure 2. 1 Classification and decomposition of exergy according to its energetic origin.

Table 2. 1 Comparison of Energy and Exergy (Gundersen, 2009; Dincer and Rosen, 2012; Gonçalves, 2013).

Energy	Exergy
Is dependent on properties of matter or energy flow only and independent of environment properties	Is dependent on properties of both matter or energy flow and the environment
Has values different from zero when in equilibrium with the environment (including being equal to (mc^2) (m=mass(kg) and c=speed) in accordance with Einstein's equation).	Is equal to zero when in the dead state by virtue of being in an incomplete equilibrium with the environment
Is conserved for all processes, based on the FLT (first law of thermodynamics)	Is conserved for reversible processes and not conserved for real processes (where it is partly or completely destroyed due to irreversibility) based on the SLT (second law of thermodynamics)
Can be neither destroyed nor produced	Can be neither destroyed nor produced in a reversible process, but is always destroyed (consumed) in an irreversible process
Appears in many forms (e.g., kinetic energy, potential energy, work, and heat) and is measured in that form	Appears in many forms (e.g., kinetic exergy, potential exergy, work, and thermal exergy), and is measured on the basis of work or ability to produce work
Is a measure of quantity only	Is a measure of both quantity and quality

2.1.7 Reference Temperature (T_o)

It represents the surrounding temperature that is considered the reference temperature in all calculations. In buildings, it is the ambient temperature which can be taken as a constant in a static analysis and as a variable in a dynamic analysis (Çengel and Boles, 2011; Mahlia et al., 2011). The exergy value is always defined relative to a given reference temperature.

2.1.8 Dead State

When a system is in equilibrium with its surrounding, the state of the system is called "dead state," and the exergy value of the system at this state equals zero (Pons, 2009; Çengel and Boles, 2011; Dincer and Rosen, 2012). In this state, the mechanical, thermal, and chemical conditions between the system and the environment are in equilibrium. The system also has no motion or elevation relative to the coordinates of the environment (Bejan, 2002). Under this state, there is neither the possibility of a spontaneous change within the system or the environment nor an interaction between them. A particular dead state is called a "restricted" dead state when only a mechanical and thermal equilibrium occur between the system and its environment. In the restricted dead state, a given system has no mass flow exchanges, both velocity and elevation relative to the environment coordinates are zero, and the reference temperature and atmospheric pressure are respectively T_0 = 25 ºC and P_0 = 101.3 Pa (Çengel & Boles, 2011). The exergy analysis results are usually sensitive to variations in dead state conditions. Some authors have conducted sensitivity analyses on the effect of varying dead states in engineering systems. Rosen and Dincer described the sensitivity exergy parameter with a reference environment based on pressure and temperature. The results indicate that, when the state is significantly different from the chosen dead-state, the exergy flows are not very sensible to the reference state choice (e.g. power plants). However, when the properties of the system are close to the reference environment (e.g. space heating and cooling of buildings), strong variations are obtained (Rosen & Dincer, 2003).

Improving the quality match between the energies of supply and demand was the introduction of the exergy concept for use in building. In most cases, high energy sources are used to satisfy low exergy need (Sakulpipatsin, 2008). So, if high quality energy is used as a source, the losses of such kinds of processes will be reduced. A measure of the quality of different kinds of energy is exergy. From this point of view, using exergy in building has been started (Hepbasli, 2012).

2.1.9 Marginal Abatement Cost Curve (MACC)

It is a tool usually adopted in low carbon strategies such as (Nationals Communications NCs, Nationally Appropriate Mitigation actions NAMAs, and United Nations Framework Convention on Climate Change UNFCCC). It is the most common tool that used to identify the Green House Gas (GHG) mitigation options (Cervigni *et al* 2013). A graph that indicates the cost, associated with the amount of emission abatement for varying amounts of emission reduction (in general in tons of CO_2). Therefore, a baseline with no CO_2 constraint has to be defined in order to assess the marginal abatement cost against this baseline development. Moreover, it allows decisionmakers to choose the best option of the cost of the abated unit of CO_2 for a defined abatement level while obtaining insights into the total abatement costs through the integration of the abatement cost curve. Because of their simplicity in a presentation of the economic and climate change alleviation, they become popular with policymakers (Kesicki 2011, Ibrahim and Kennedy 2016). Moreover, it has been used in various options on different economic aspects (Timilsina *et al* 2017).

The MAC tool that was developed by Timilsina et al. is simple and can be used for any country interested to use. To explain its simplicity and its usefulness, its specifics are detailed in Figure 2.3. The X-axis represents the amount of CO_2 emission in ton. It can be noticed that in all (positive/Negative) alternatives processes the value of carbon dioxide is positive. The consequent costs of all alternatives are represented by Y-axis. The alternatives that cause negative results, their costs are positive whereas, those that their effects are positive their costs negative. That means the alternatives that have negative costs mitigating the carbon dioxide and consequent the cost. Based on the same interpretation, the alternatives that have positive cost heighten the CO_2 production and the cost. The alternative processes that have zero costs represent the adopted standards by the country, so the alternatives are measured relative to it.

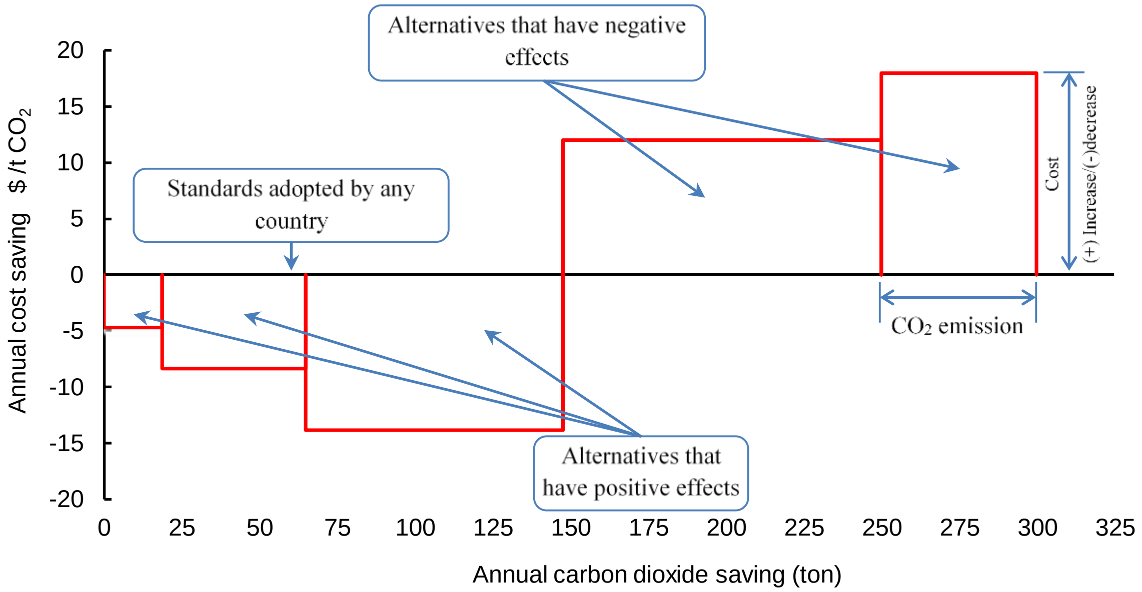


Figure 2. 2 Detailed explanation of Marginal Abatement Cost Curve (MACC)

In Figure 2.2, a scheme of energy quality flows in buildings is represented on the supply and demand side. The fossil energy supply and related energy use for building demand are represented. The size of each arrow gives an indication of the magnitude of each energy flow. A close match between supply and demand levels could be achieved through the use of suitable energy sources chosen according to the demands of the building, increasing overall exergy performance significantly (Torio and Schmidt, 2011). To achieve this goal, buildings should be designed to operate with sustainable energy sources for both heating and cooling at adequate temperature levels. Low-temperature heating systems and high-temperature cooling systems are considered to be some of these positive ideas that lead to improving building performance. All these ideas lead to the low-exergy thought (Schmidt, 2004b; Schmidt and Ala-Juusela, 2004; Schmidt, 2009; Hepbasli, 2012).

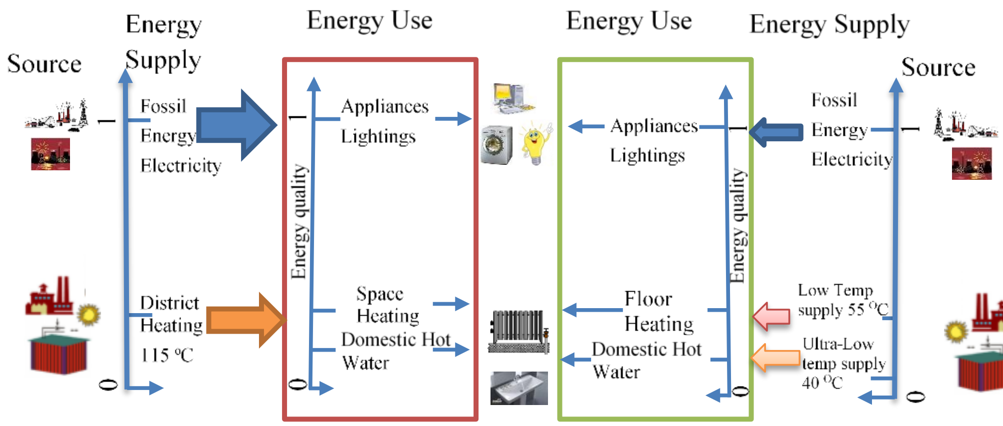


Figure 2. 3 Schematic view of energy flows in buildings (Schmidt, 2009):

Left: traditional building

Right: low energy building

2.2 *Applying Exergy Analysis to Building*

Many researchers have explored the exergy demand in buildings while others have focused on an exergoeconomic analysis; however, both are essential to in this case. For instance, Schmidt (2004b) presented a clear, comprehensive, and relatively simple methodology to explain the energy and exergy flow from the transformation till they are consumed in the building. A pre-design tool for buildings has been used to perform this concept based on a combination of the first and second laws of thermodynamics. He proved that energy analysis alone is not sufficient and will not provide a full conception of all influential components that contribute to energy consumption. In addition to the concept explanation, he added examples that made the concept easier to understand and applicable for designers. Furthermore, based on his article, the first priority should be given to finding a high-performance envelope and the second to finding a service system which would lead to achieving the best performance.

For instance, Bejan (2002) outlined the fundamentals of the methods of exergy analysis and entropy generation minimization (Bejan 2002). He illustrated the concept of irreversibility and exergy destruction and submitted examples that explained the accounting for exergy flows and accumulation in closed systems, open systems, heat transfer processes, and power and refrigeration plants. Based on his results, the relation between exergy and entropy generation gives the designers an opportunity to determine the hindrances and environmental conditions for such analysis. In addition to the fundamentals of exergy analysis, Balta et al. estimated the performance of a building of 351 m^2 and net floor area of 117m^2 for four options of heating applications (heat pump, condensing boiler, conventional boiler, and solar collector) which were driven by renewable and non-renewable energy sources (Balta et al., 2010). The flow of energy for each option was calculated. The overall exergy efficiencies of those options are 3.66, 3.31, 2.91, and 12.64%, respectively, whereas the sustainability index values for those options are 1.039, 1.034, 1.03, and 1.144. The results show that the performance of the fourth option is the best (Balta et al., 2010).

Mahlia et al. (2011) showed the energy use for daylight, electric lighting, and space cooling systems as a series of exergy input, output, and consumption (Mahlia *et al* 2011). They showed how daylight consumes solar exergy and how electric lighting and space cooling systems consume exergy from fossil fuel. These researchers developed a method that is applied to the lighting and cooling of an ideal room. According to the results, the lowest amount of exergy was consumed by electric lighting while the highest amount was consumed by space cooling. Hepbasli (2012) conducted a comprehensive review of low exergy heating and cooling systems and applications for sustainable buildings and societies (Hepbasli 2012). The article consists of a summary of the energy utilization and demand in buildings, a description of various exergy definitions and sustainability aspects along with the dead state, an introduction of low cooling and heating systems, and a presentation of the low exergy relations used to determine the energy and exergy demand in buildings. The exergy efficiency values of the low exergy heating and cooling system for building were calculated as 40% to 25.3% while those for greenhouses varied between 0.11% and 11.5%, and the main analysis and assessments of low exergy systems were dependent on the heating of buildings.

As a part of improving the exist building, Jansen et al. (2012) presented the exergy performance of a social dwelling of a multi-family building from the 1960s in Bilbo, Spain and proposed and investigated improved energy concepts according to smart exergy use (Jansen *et al* 2012). The usefulness of the exergy approach in assessment and development of an energy system for dwelling under consideration were explored and demonstrated in the cases are presented in this study. The first case was the original situation, second one assumed use of the usual retrofitting, and the final, improved case was based on exergy concepts. According to the results of the study, exergy analysis revealed that thermodynamic losses that cannot be determined depending on energy analysis and a significant reduction in primary building energy can be achieved if the energy system is developed based on exergy principles. In order to show the usefulness of the exergy analysis method, Wierciński and Aldona (2012) used the exergy balance next to the energy balance for the estimation of different kind of buildings (Wierciński and Aldona 2012). This method was, firstly, applied to a traditional house that uses a boiler and steam radiators for heating and, secondly, to a low-energy building that uses a heat pump and air heating instead of a boiler and radiators in order to explain the differences in heating systems that used in these buildings. According to the results, the exergy destruction for the low-energy house is lower than for the ordinary one.

Contrary to what has been done before, Nurdan and Hepbasli (2014) compared two types of systems that are usually used to heat houses, the condenser boiler and the heat pump, for the same house based on energetic and exergetic analyses (Nurdan and Hepbasli 2014). The house was located in Izmir, its volume was 326.7 m^2, and its floor area was121 m^2. The indoor and outdoor temperatures were 20^o C and 1^o C, respectively. The results showed that the total heat loss rate was 3770.72 W. The overall energy efficiencies of the two cases were 49.4% for the condenser boiler and 54.7% for the air heat pump. The overall exergy efficiency, the flexibility factor, and the sustainability index were 3.3%, 0.17% and 1.034%, respectively. The same field was studied by Wei and Zmeureanu (2009), but they applied it to two types of variable air volume (VRV) systems instead of traditional ones (Wei and Zmeureanu 2009). These systems were used for office building air-conditioning in Montreal. A mathematical model was been developed by using the EES program to determine the energy and exergy efficiencies and the CO_2 emissions that were produced due to the generation of the required electricity. They found unexpected values of exergy efficiency in those two systems, which was around 2-3%. According to their results, there is a real need to improve this type of conditioning system because of their low exergy efficiencies; the best way to improve the system can be achieved by using an alternative heating source such as a renewable energy source instead of electricity. In the same year another study presented energy and exergy analyses of space conditioning of a building in Izmir (Yildiz and Güngör 2009). They did not take the cooling load of the building into account. The volume of building given as an example was 720 m^3 and the net floor area was 240 m^2. The interior and exterior temperatures are considered to be constant at 20^o C and 0^o C, respectively. They studied three scenarios for heating the building: the LNG conventional boiler, the LNG condensing boiler, and an external air-air heat pump. Energy and exergy flow and losses were determined for the whole system.

After that Lohani 2010 submitted energy and exergy analyses of fossil fuel plant and heat pump building heating systems at two different dead state temperatures (Lohani, 2010). He used software package IDA-ICE to carry out the fossil plant heating system simulation whereas there was not a simulation model for a heat pump in the program. Five cases were studied in this context: a conventional system, a ground coupled heat pump integration system (30^{o}C), a ground coupled heat pump integration system (40^{o}C), an air source heat pump integration system (30^{o}C). The results show that the ground source had a better performance than the others.

For the same purpose but in different way, another model was presented for a building that was considered like a black box by Lorenzo (Lorenzo 2014). Another difference was that this study considered the matter fluxes that are functional for the building needs previously defined in addition to energy flux. It was not possible to carry out the model of individual components that made up the system, but it allowed for comparing of different building energy configurations. A description of the model was explained, and the thermodynamic interaction the building and its surrounding was analyzed in order to evaluate the input exergy, loss, and destruction exergy. A computational model was added in this study. In the same year, Tian (2013) submitted a comprehensive review of sensitive analysis methods in building energy analysis (Tian 2013). He concentrated on the application of these types of analysis in the field of building performance analysis. He described the typical steps of implementation of the analysis in the building. Furthermore, he discussed many topics like input variables determination, building energy program choices, and reduction in the computational time of energy models. In addition, to discussion, he reviewed the sensitive analysis methods used in the building field and organized them. The article also discussed several topics include application of a sensitive analysis in an observational study, how to deal with correlated inputs, the computation of variations in a sensitive index, and software issues. Lastly, based on the advantages and disadvantages of those analyses, a practical guide was given for estimating building thermal performance. In order to find possible opportunities leading to a decrease in energy consumption in Turkey, an existing building was studied (Akdemir, 2013). The building was the Izmir Institute of Technology (IZTECH). He used the EDSL-TAS energy simulation software package to perform dynamic energy analysis of the building. Simultaneously, an exergy analysis was applied dynamically for the same purpose. The analyses were applied to the states before and after building renovation. The results revealed that the energy building performance and its climatic comfort increased substantially. Furthermore, the building demand energy loads decreased 69.42% in the winter while the reduction percentage in summer was 34.4%. Three systems were examined, and their exergy efficiencies ranges were 2-14%, 4-18%, and 8-21% for existing HVAC, air source heat pump, and ground source heat pump (GSHP), respectively. Teres-Zubiaga et al. (2013) presented a study explaining the benefits of the exergy approach in the development of energy systems (Teres-Zubiaga *et al* 2013). They examined five energy systems for a building in Spain where two of them were references cases while the other was proposed as options. In the article, a dynamic analysis was applied where the energy and exergy losses of the system components were determined in addition to their efficiencies through all the system components from energy demand to the resources. Furthermore, some improvements were explored based of that analysis. Lastly, they concluded that applying exergy analysis could be useful for giving good figures about exergy losses in a form that led to further reductions in energy demand. Gedso and Petersen (2016) wanted to check the validity of software applications results, so they examined the efficiency of using some software applications that were based on BIM tools for the determining of the heating and cooling loads of the buildings (Gedso and Petersen 2016). In other words, they investigated whether such applications were accurate enough to be applied in such a field based on Norwegian standards. They used NS-EN 12831 as a reference in addition to Revit MEP, MagiCAD Comfort and Energy and IDA ICE. They deduced that the applications developments were in the correct stream; however, there were some limitations in their accuracy. Furthermore, the results could include essential errors unless the users of the applications were experts in such calculations. Exergoenvironmental analysis for an existing heating system from the generation stage to the building envelope for evaluating the components' environmental impacts was completed by Acikkalp et al. (Açikkalp *et al* 2015).

The importance of energy and exergy analysis was clearly shown clearly from previous studies and that is what Biserni and Cesare (2015) highlighted in their article (Biserni and Garai 2015). They found that the exergy concept provided good flexibility for strategies to make the building design better. The study, based on the first and second laws of thermodynamics, turned out to be the most extreme generality of the two laws that prove the fact, in thermodynamics, any system is a black box without any information related to design, organization, or evolution. This study outlined the introductory analysis of the potential of nonstructural theory in order to estimate the energy performance of the building.

Bicer and Dincer (2016) applied the energy and exergy method to a new renewable energy system based on multi-generation (Bicer and Dincer 2016). It includes PV/T and geothermal energy systems, which provide electricity and heating power, heating, cooling, hot water, and drying air. The performance of this design was estimated. The overall efficiencies were 11% and 28%, respectively. The effects of environmental and operation conditions on the efficiencies were also studied. Furthermore, the exergy analysis was widely applied to hotels and student accommodation buildings in order to highlight and demonstrate its significance in such fields and systems by Gonçalves (Gonçalves 2013).

The first case of five cases he studied was concerned with a reference state which was calculated based on average outdoor temperature for a specific period. He estimated and compared energy and exergy ratios, and he found that, for different reference states, exergy analysis was more significant than energy analysis.

In order to make the results understandable and comparable, some researchers used the Marginal Abatement Cost Curve (MACC) methodology which is widely used in climate change policies. Policymakers rely on MACC to assess feasible strategies and related costs in achieving emission reduction goals (Kevin et al., 2016). Wachter (2013) presented CO_2-emission reduction options by drawing a MACC for Austria and by critically assessing the applicability of such curves to real economic analyzes (Wächter 2013). He discussed various high-impact scenarios for reducing emissions for the household, service, transport, and energy supply sectors. He found that MACC provided a quantitative basis for decision makers in which abatement measures could be pursued and conducted in terms of their overall potential and how much they would cost. Xiao et al. (2014) developed an improved bottom-up model to illustrate the carbon abatement potential and MACC for 34 selected energy-saving technologies/measures for China's building sector (Xiao *et al* 2014). They found that strengthening successful energy-saving technologies is important, especially for the residential building sector. Moreover, Timilsina et al. (2017) developed a methodology for estimating MACC for energy efficiency measures and applied it to the building sector in Armenia and Georgia (Timilsina *et al* 2017).

2.3 *Applying Exergoeconomic and Environmental Analyses to Buildings*

In order to connect the loss with the cost, it is important to start with the definition of exergoeconomic. It is the branch of engineering that connects the components and processes of the system and the thermodynamic estimation depending on an exergy analysis with economic principles. It is an efficient method that gives the designers and operators of a system an opportunity to optimize the components and processes in order to achieve a cost-effective-system (Tsatsaronis, 2007). In case of exergoeconomic analysis, many studies have been published. Tsatsaronis et al (2013) submitted an essential study that explained the exergy-based method which allows researchers to connect between many aspects related to inefficiencies like exergoeconomic, and environmental analyses (Tsatsaronis *et al* 2013). This method gives a real figure for how the efficiencies of productive power plants, I. C. engines, manufactures, and buildings affect the world economically and environmentally. Sevilgen and Sancar (2011) developed new model in order to estimate the best capacity of the tri-generation system that increases the present profit (Sevilgen and Sancar 2011). Their model depended on adding the tri-generation system to the existing system and making an optimization to determine the best use of the system. The model was employed on a university campus. The calculation and optimization were confirmed by energy analysis. The electricity demand of heat and cooling are considered in addition to the information for the existing building system. It was found from the results that the tri-generation system provided 84% of electricity demand, 71.9% of heat demand, and 62.9% of cooling demand, whereas the rest of the demands are provided from the existing system. Depending on results, the payback period would be 10 months.

On other hand, Yucer and Hepbasli (2014) estimated the exergoeconomic, and enviro economic performance by applying a specific exergy costing method (SPECO) to a building heating system (Yücer and Hepbasli 2014). The exergetic cost effectiveness (ECE) was used in the article to determine the most effective parts that should be improved. They found that the highest amount of destruction happens in generation and the building envelope which were 0.569 and 0.0057, respectively. They concluded that the analysis based on static conditions might not achieve the aimed for accuracy compared to a dynamic analysis, so it was better to do a dynamic analysis instead of a static one. In addition to dynamic analysis, they claimed that using modern building simulation programs to utilize the analysis might produce better results. Caliskan (2016) applied the LowEx analysis to a building with a ground source water to supply the heat pump that was used to heat the building's 225 m^2 area and 675 m^3 volume (Caliskan 2016). The building was heated by a floor heating system to keep its temperature at 23^{o}C while the ambient temperature was 0^{o}C. The heat demand was 2915.55 W while the energy and exergy efficiencies of the system were 33.08% and 4.47%, respectively. He concluded that there was a real necessity to apply low exergy analysis to estimate the system through the full thermodynamic aspects.

The main contribution of this work can be summarized by these points.

1- Presenting the exergy and exergoeconomic analyses in one simple method that can be applied to any building or productive device.
2- Investigating the difference between the static and dynamic analysis and opportunity to minimize the deviation between their results.
3- Analyzing an actual very large building that represents the case study.
4- Estimating the feasibility of real improving processes that were added to the building in different stages.
5- Constructing the Marginal Abatement Cost Curve (MACC) for all applied scenarios.

CHAPTER III

APPLICATION TO A COMPLICATED HIGH-PERFORMANCE BUILDING

The SCOLA (School of Languages) Building is a part of the master plan of Özyeğin University, which is situated in Nisantepe in Istanbul in north-west Turkey (Figure 3.1). This building was constructed in 2013 with partial support from the European Union Seventh Frame Program with the NEED4B (New Energy Efficiency Demonstration for Buildings) Project (NEED 4B, 2018). It was designed to be one of the most energy efficient buildings in Turkey. Some features of the building are highlighted in Figure 3.2. The advantages of the building and the new technologies that are be explained below.

Figure 3. 1 The SCOLA Building, Ozyegin University, Istanbul, Turkey

3.1 *Building Description*

The Scola Building has features that make it one of the smallest energy consumers in Turkey. It was designed well with good components in order to achieve this goal. Figure 3.2 shows the schematic of the building and its features. The details are found below (NEED 4B 2018):

Building Structure and Envelope

Reinforced concrete frame construction was selected for the main structure. Various solar shading devices were installed, designed according to the façade they are mounted on. The average U value is 1.6 W/ m^2 K for the total envelope area. Walls are 0.302 W/ m^2 K, the roof is 0.248 W/m^2 K, and the ground floor is 0.568 W/m^2.

Opaque Surfaces

Generic exterior walls: plaster 1.2 cm + BIMS bricks 15 cm + EPS 8 cm + cement mortar 1 cm + paint and walls penetrating the soil: plaster 1 cm + drainage panel 2.5 cm + BIMS bricks 15 cm + EPS 3 cm + levelling concrete 1 cm + reinforced concrete 30 cm (No 2 in Figure 3.2).

Roof

Pebble 5 cm + drainage panel 2.5 cm + reinforced concrete 5 cm + EPS 10 cm + bitumen 0.6 cm + reinforced concrete 12 cm.

Floor in Contact with Ground

Finishing 2 cm + levelling concrete 3 cm + reinforced concrete 50 cm + drainage panel 2.5 cm + levelling concrete 3 cm + EPS 3 cm + bitumen 0,6 cm + reinforced concrete 30 cm.

Transparent Surfaces

Double glazed, low-e type glazing with U-value of 1.6 W/ m^2 K at north facade and 1.3 W/ m^2 at other facades. At the north façade, comfort 4+16+4 glazing and aluminum framing with Sc=0.9 (shadowing factor). At the south, east and west façade Guardian SunGard Super Neutral 5/28 4+16+4 glazing and aluminum framing with Sc=0.33 (shadowing factor) is installed. This decreases the need for mechanical cooling significantly.

Shading Elements

Various solar shading devices were installed, designed according to the façade they are mounted on. The sun breakers' design was supported by running many simulations. Horizontal louvres were installed at the south façade, perforated sun breakers horizontal at south façade and partially at east façade. Vertical perforated aluminum shades were in the other facades according to the simulations, and internal curtains, where necessary. There was an agreement among all the stakeholders from the beginning for the same style of sun breakers to be used throughout the campus. Mock-ups were installed at the different facades of the building and approved by a team of stakeholders prior to implementation of all façade elements.

Heating System

This feature was detailed in Section 3.2.

Ventilation and Cooling System

The information is in explained in Section 3.2.

Lighting System

The lighting system is totally automated which enables almost 35% in energy savings. Different sizes of LED armatures with 40W power and T5 armatures were designed according to the application area. The energy density changes between 3.3 – 5.8 W/m². The installed capacity is 79 kW, and the yearly lighting power is 152.208 kWh. The consumption density of the lighting system is 9.4 kWh/m² without automation and 6.1 kWh/m² with DALI automation. The overall lighting system consumption can be covered by the 126kWp PV system on the roof of the building which means that all lighting systems are supplemented by sunlight. Thus, utmost importance was given to maximum usage of daylight.

PV Panels Instillation

This feature is in detail in Chapter 3, Section 3.1.10.

Earth Tube or Ground Air Heat Exchanger (GAHX)

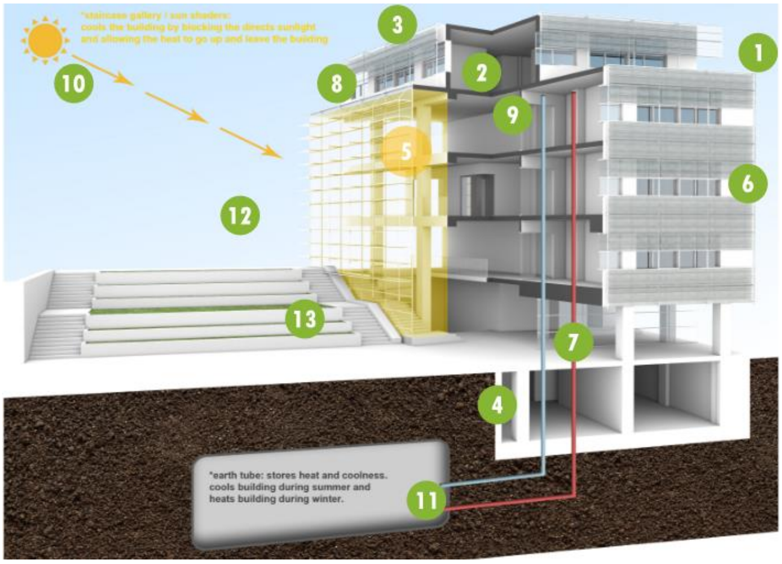
Details of the GAHX can be found in Chapter 3, Section 3.1.11.

Monitoring System

The building has a Multi-dimensional Energy Performance Monitoring, Visualization and Optimization Platform (Figure 3.14). Sensors, meters, and transmitters are installed to measure different end-uses (lighting, heating, ventilation, PVs, etc.), allowing full control of HVAC and lighting systems. There are LCD screen for displaying instant data of the building's performance. Building Energy Dashboards are displayed, enabling, engaging, and energizing building occupants to save energy by provision of real time monitoring. The screens make real time energy flow visible, accessible, and engaging so that building occupants get the data visualization tools to manage and reduce their energy consumption.

Other solutions

This feature consists of some processes that adopt recycling things as much as possible. collecting the rainwater and treated it to be reused in baths and irrigation purposes represents one of them.



[1] Building Structure and Envelope
[2] Opaque surfaces
[3] Roof
[4] Floor in Contact with Ground
[5] Transparent surfaces
[6] Shading Elements
[7] Heating
[8] Ventilation
[9] Lighting
[10] Monitoring System
[11] Ground Air Heat Exchanger
[12] PV installation
[13] Other solutions

Figure 3. 2 Features of the SCOLA building that improve its performance. (NEED 4B 2018).

3.2 *The Conditioning System*

The conditioning system of the SCOLA Building consists of a 2,200-kW boiler for heating, a 2,000-kW centrifugal chiller for cooling, a distributive pipes network .and 420 four pipe fan coils of different capacities adopted to heat the rest of the floors. The floors above the ground are ventilated naturally; however, a mechanical exhaust system is also present. Figure 3.3 explains the schematic diagram of main parts of the SCOLA conditioning system. The details of the boiler and chiller are explained in Figures 3.4 and 3.5.

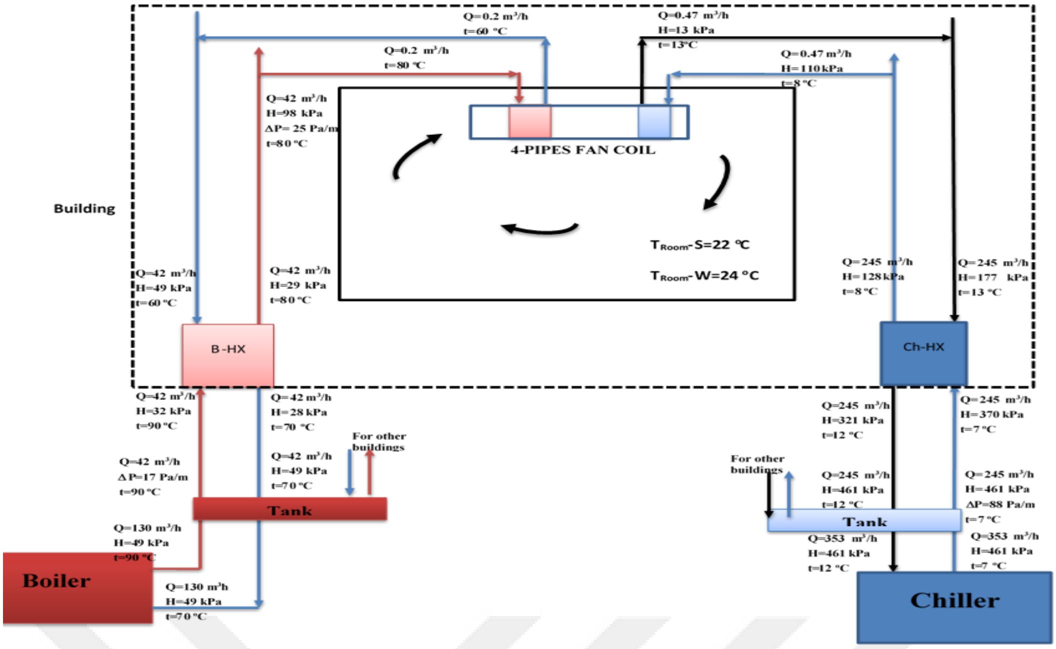
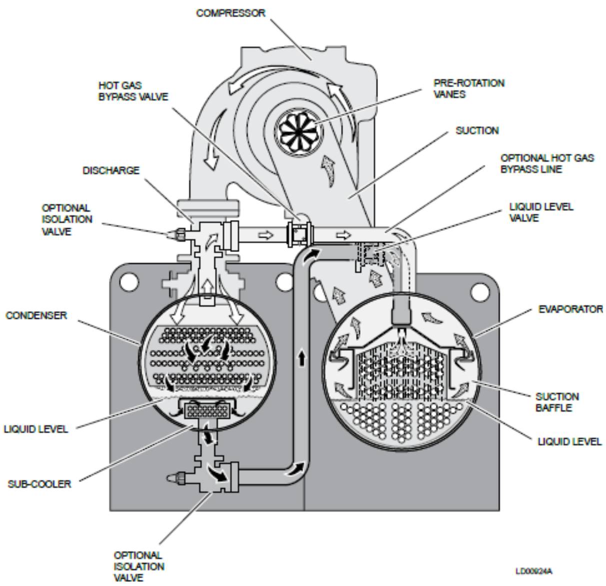


Figure 3. 3 Schematic diagram of the of the SCOLA Building conditioning system.

Boiler	
Type	Gas boiler
Model	Hoval -Max-3 plus
Capacity (kW)	2200
Fuel type/consumption (kg/h)	Natural gas /180
Water temperature inlet/ outlet (ºC)	70/90
Water flow rate (m^3/h)	113

Figure 3. 4 Gas boiler that is used for the SCOLA Building



Centrifugal chiller	
Type	Liquid chiller
Model	YK (STYLE H)
Capacity (kW)	2000
Cooling gas	R-134a
Chilled water inlet and outlet (°C)	12/7
Water flowrate (m^3/h)	345

Figure 3. 5 The Centrifugal chiller of the SCOLA Building

Figure 3.6 provides good understanding of the energy consumption or how the energies are consumed in the original case (the first case) or in the current state without any improvement in the conditioning system. However, architectural improvements still applied.

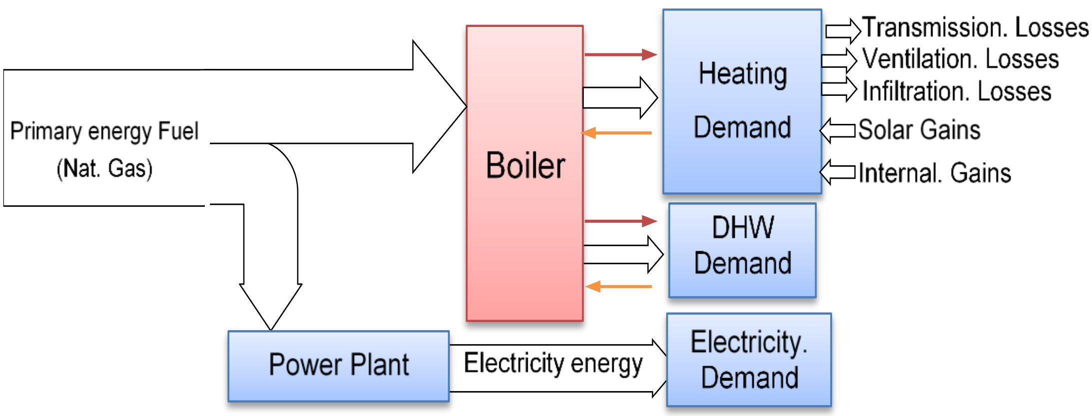


Figure 3. 6 The building energy flow of Case 1.

3.3 *Improving Processes*

In order to improve the performance of the building and reduce energy consumption, some ameliorative processes were added to the building system. Some of them reduce the heating load of the building by using an underground heat exchanger (earth tube), others exploit solar energy to decrease electric energy consumption, and some of them replacing the energy source itself by using the tri-generation system. The details of all these processes are explained in following paragraphs.

3.3.1 Underground heat exchanger (Second Case)

The second case is adding a ground air heat exchanger that leads to a reduction in the heating load. Ground air heat exchangers are being used for partial cooling/heating of the facility ventilation air. Supply air is provided by natural ventilation in the building. In order to provide acceptable indoor air quality a mechanical exhaust system supports the system. The horizontal air-ground heat exchanger system is installed on the eastern side of the building. The system installation area covers approximately 1,200 m^2 of land and is installed at a depth of 2 m with 72 m long horizontal pipes and 10 m width. The heat exchanger is, so far, the largest installed system in Turkey. Figure 3.7 explains some images of stages of the system's construction. Its contribution is 15% of the total heating load (NEED 4B, 2018) and that leads to improvement in the performance of the building. This step affects the heating load directly. The energy demand and its consequent costs and CO_2 emission reduce due to this process. Figure 3.8 explains the schematic diagram of the ground air heat exchanger. Moreover, Figure 3.9 represents the schematic diagram of this improvement processes, the second case that will be analyzed.

Figure 3. 7 Construction stages of the underground heat exchanger and the sensors being added inside pipes.

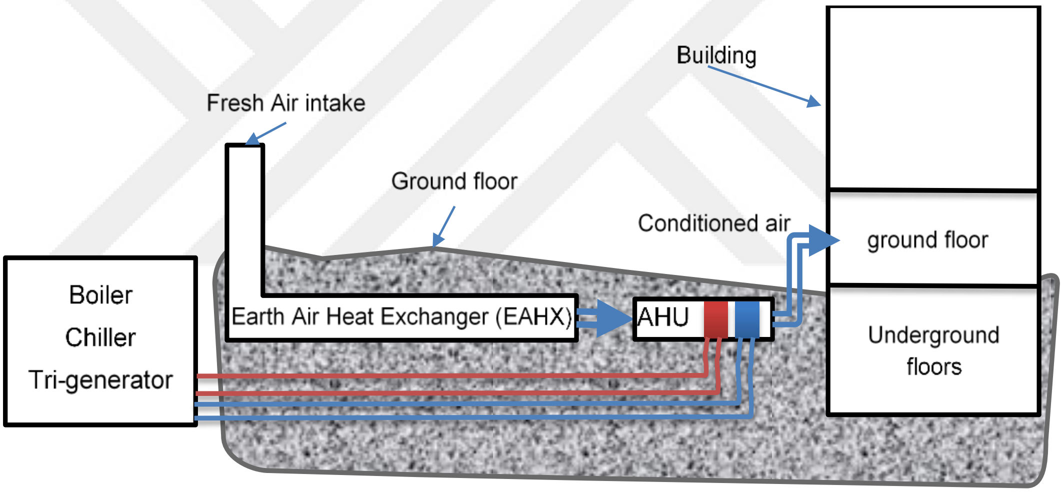


Figure 3. 8 Schematic diagram of the Ground Air Heat Exchanger (GAHX) position and the air stream.

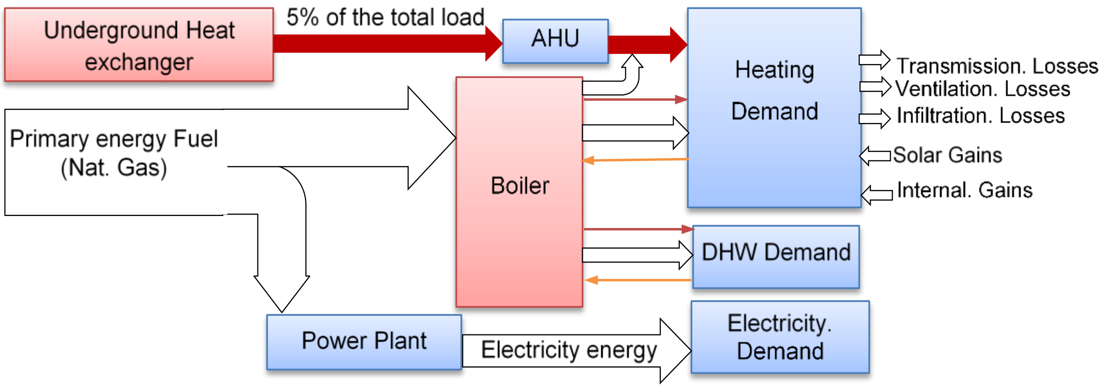


Figure 3. 9 The building energy flow of Case 2.

3.3.2 Architectural Effects (Third Case)

In this case, three improvements in overall heat transfer coefficients are assumed. The U-overall of walls, windows, and roofs are reduced 50%, 23%, and 25%, respectively. The potential enhancement of the building thermal performance due to these changes has been investigated. It considered to be the third case. This case investigated separately in detailed way in section 5.2 to highlight the architectural effect on the performance of the building.

3.3.3 Photovoltaic Panels (Fourth Case)

504 Pieces of PV model with efficiency 15.4% Covering 75% of the roof area by photovoltaic system based on multi-crystalline silicon technology is the third case. Its type is *Yingli YL250P-29b* and its general output is 106 kW with 6 inverters that transfer DC to AC power. Its orientation to the south is 0ºC and panel tilt 15º. The contribution of this improvement is reducing the electricity demand and also its cost and pollution impacts. Its real image can be seen in Figure 3.10. The hourly AC-power that is produced by photovoltaic cells was provided by the SCOLA university. There are 6 inverters that convert the DC power to AC their details can be seen in Table 3.1. For greater accuracy, the actual AC measure of electric power was obtained for this purpose. The hourly values for the entire year are shown in Figure 3.11 (NEED 4B, 2018). Also, how this process was

connected to the building system can be noted in Figure 3.12, which represents the fourth case of this study.

Figure 3.10 PV panels on the roof of the building

Table 3. 1 Details of PV cell invertors

INV_Number	INV-type	Serial	AC power (W)	Daily energy (kWh)	Total energy (kWh)
Inv-1	REFUsol 020K	80132029	4782	3.6	100476
Inv-2	REFUsol 020K	10010179	4504	3.4	93647
Inv-3	REFUsol 020K+	80146811	4661	3.3	105124
Inv-4	REFUsol 020K+	80146812	4345	2.7	97940
Inv-5	REFUsol 020K	80131213	4785	4.1	103821
Inv-6	REFUsol 020K	10032368	4788	3.2	105478

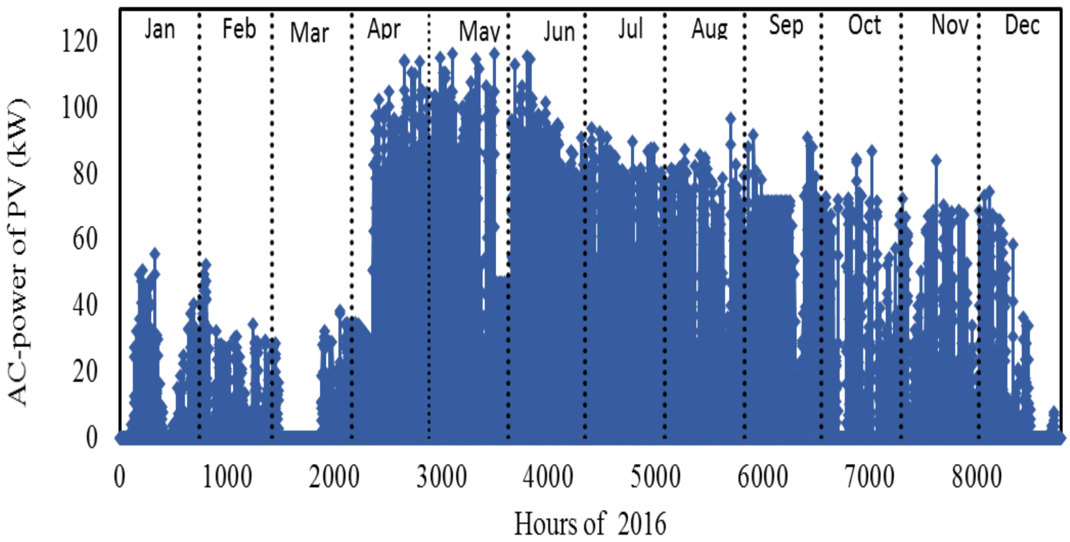


Figure 3. 11 The actual AC power output of SCOLA PV cell.

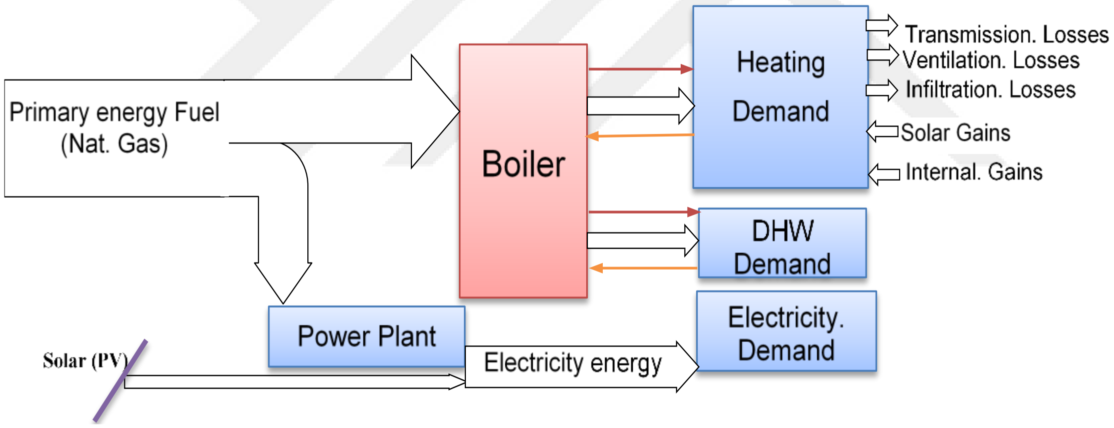


Figure 3. 12 The building energy flow of Case 4.

3.3.4 Tri-generation System (Fifth Case)

The most significant improvement for the building was achieved after adding a tri-generator system which simultaneously provides electricity and works as both a heating and cooling source. The tri-generator produces these three types of energies for the whole university campus includes which the SCOLA Building. Figure 3.13 indicates the general mode of the tri-generator and how it provides these types of energy to the university campus. In this study, the heating mode was investigated, i.e. the tri-generator production of electricity and the heating of water. Figure 3.14 depicts the energy streams through the building system. All the real-time data of the tri-generator was provided by Ozyeğin University.

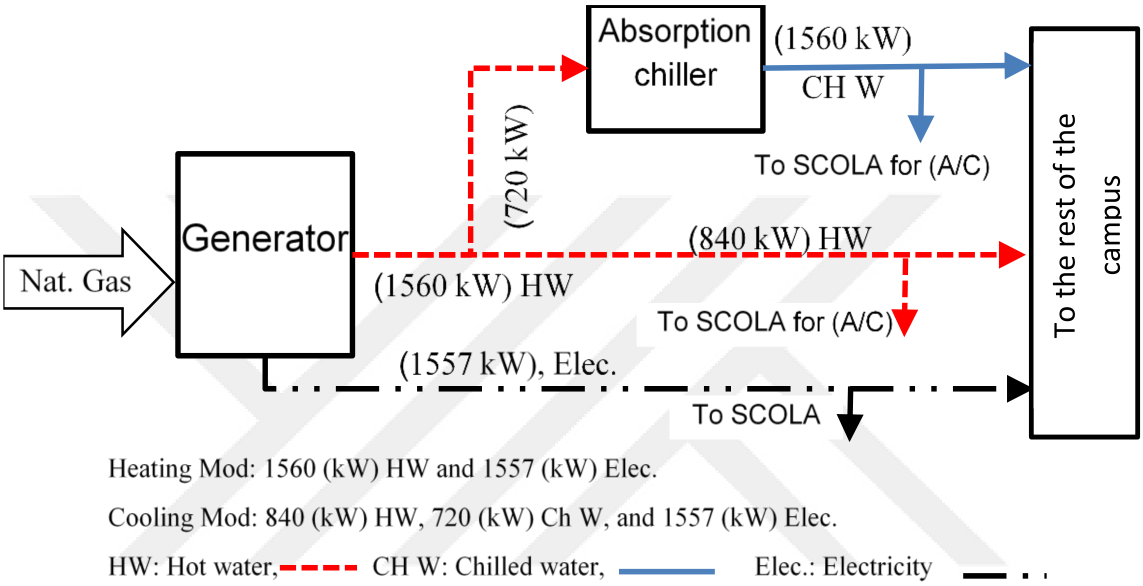


Figure 3. 13 The Tri-generator operation details for both modes. In general mode, the tri-generator produces three energies (electricity, hot water, and chilled water.

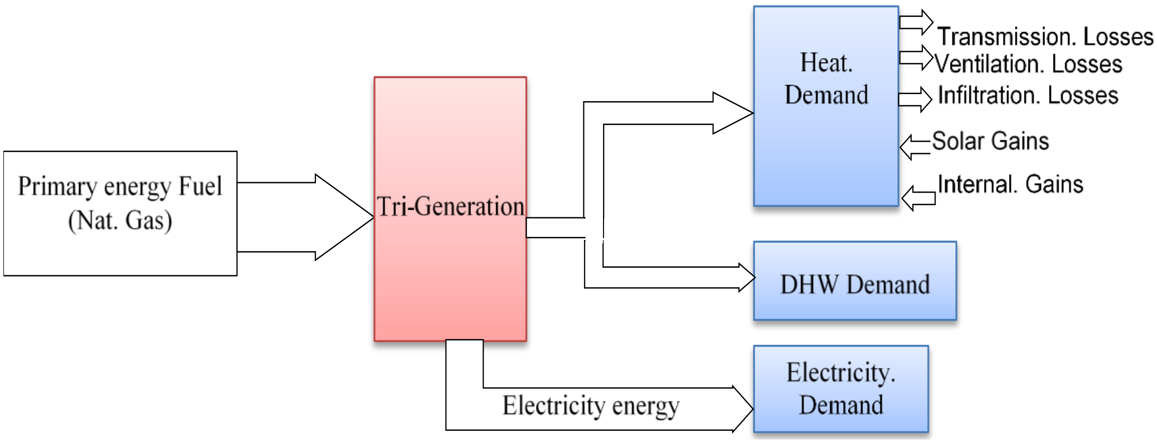


Figure 3. 14 The building energy flow of Case 5.

In this work, applying all improving processes (the second, third, fourth, and fifth cases) to the first case was considered the sixth case. In this case, in addition to tri-generator use as an energy source for both electricity and hot water, the effects of the architectural aspect, the underground heat exchanger and solar energy (PV-panels) are added to the tri-generator impact. This leads to more reduction in energy demand and less CO_2 emissions. A comparison between all these cases will be presented based on dynamic energy, exergy, exergoeconomic, and environmental analyses.

CHAPTER IV

MATHEMATICAL and NUMERICAL ANALYSES

Here, a mathematical model is presented as discussed in different studies above. Firstly, an energy and exergy analyses of the devices that are used to condition the building were presented. These devices are the centrifugal chiller for cooling and the natural gas boiler for heating. Secondly, the methodology to determine the energy and exergy demands of the building is presented, which depends completely on the energy demand of building and inlet and outlet temperatures. In addition, an exergoeconomic analysis that matches the exergy demand with the cost of each part of the system was also presented. Lastly, the exergetic cost effectiveness method is submitted in order to determine the effective factor in the system.

4.1 Building analysis

The main following processes in the building are two losses and gains. All of them are explained in Figure 4.1, and they are analyzed in the following schematic diagram (Schmidt, 2009).

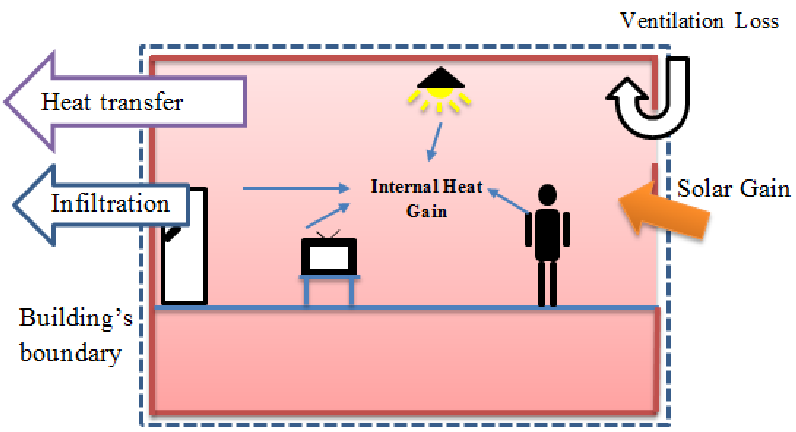


Figure 4. 1 Schematic explanation of heat gain and loss in a house.

4.1.1 Heat Transmission

Heat loss includes the heat transmitting from the wall, windows, doors, roof, and floor as well as heat loss during the ventilation and infiltration process.

Heat loss (transmitted by conduction and convection) through the building envelope can be divided into two groups. The total transmission heat loss rate is the sum of the losses from all components of the building (k) and can be calculated as

$$\dot{Q}_{trans} = \sum(U_k.A_k.).(T_R - T_o) \tag{1}$$

In summer, another factor can affect the cooling load; it happens because of the effect of the sun, and it can be estimated as follows:

$$\dot{Q}_{trans} = \sum(U_k.A_k.).CLTD \tag{2}$$

where CLTD is the cooling load temperature difference.

In order to correct CLTD for other locations

$$Correct\ CLTD = CLTD + (25.5 - T_R) - (T_o - 29.4) \tag{3}$$

There are other methods for estimating the solar flux effect on the external surfaces (walls, roofs, and frames) during the summer. Radiant time series (RTS) is one of them, which is derived by the HB (Heat Balance) method; it is an efficient method to use instead of old methods like the transfer function method (TFM), the cooling load temperature difference (CLTD), and the total equivalent temperature difference (ETD).

According to this method the energy is gained from external surfaces is equal to

$$q_{k,\theta-n} = A_k.U_k.(T_{o,\theta-n} - T_R) \tag{4}$$

where

$q_{k,\theta-n}$: conduction energy input from surface *n* hours ago.

Other symbols are explained above.

This method takes into account both conduction and radiation heat transfer:

$$T_o = T_{Air} + \alpha.\frac{I_t}{hc_o} - \epsilon.\Delta R/hc_o \quad (5)$$

$\epsilon.\Delta R/hc_o$: for horizontal surface =4 K, and equals to zero for vertical surface

where ΔR=difference between long-wave radiation incident on the surface from the sky and the surroundings and radiation emitted by a blackbody at outdoor air temperature, (W/m^2): 20 for horizontal surfaces, 0 for vertical surface (Ashrae, 2013b).

4.1.2 Ventilation and infiltration losses

The ventilation rate ($\dot{Q}_v$) can be calculated according to the enthalpy difference that takes into account the sensible and latent (Schmidt, 2009):

$$\dot{Q}_v = \rho_{Air}.V_{buil.}.nr_v.(1 - \eta_{Hrecov})(h_R - h_o) \quad (6)$$

According to Schmidt, ventilation loss can be ignored in one situation: if the required airflow rate that is supplied to the building in for cooling or heating is larger than the ventilation rate. In such cases, the loss of ventilation is canceled (Ashrae, 2013a).

Infiltration losses can be calculated in the same way for ventilation with the infiltration rate (nr_{inf}) instead of the ventilation rate (nr_v):

$$\dot{Q}_{inf} = \rho_{Air}.V_R.nr_{inf}.(h_R - h_o) \quad (7)$$

4.1.3 Internal Loads

Internal loads take many forms solar, people, appliances, and lights which have a positive effect in winter and a negative effect in summer because they reveal the heating load in winter by adding heat to the buildings; consequently, a reduction in the heating load occurs. In general, internal loads are not considered in the design because they are not guaranteed.

4.1.3.1 Solar Energy

Solar energy depends on the position of the sun, surface orientation, and surface incline, as explained in Figure 4.2.

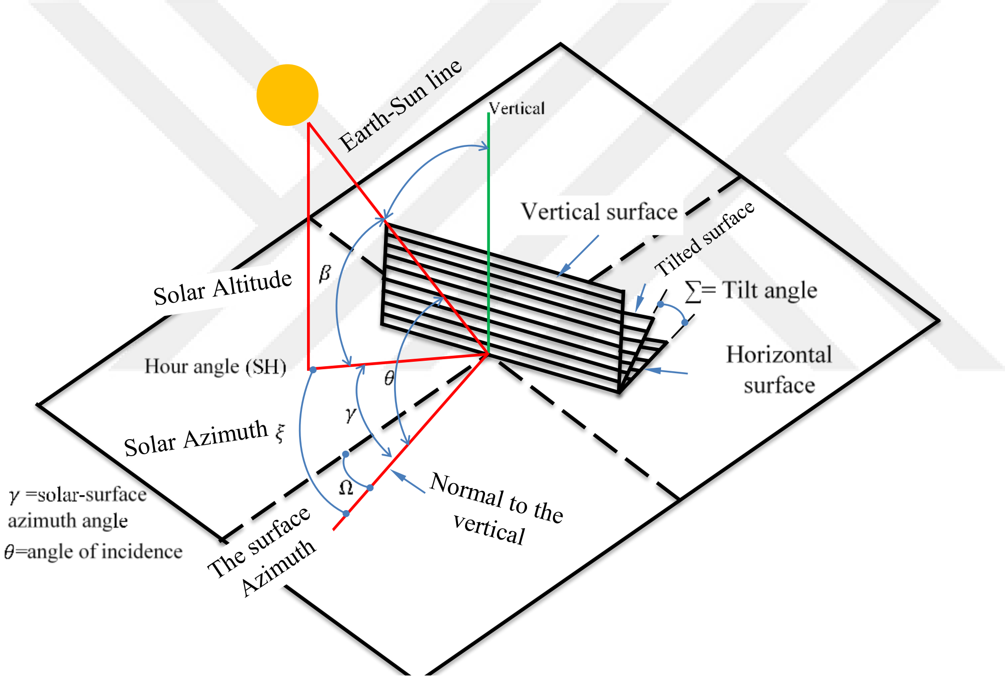


Figure 4. 2 Solar heat irradiance analysis explanations

This type of energy can be estimated by the means listed below (Ashrae, 2013b).

There are many equations that are used to determine the solar irradiance of all surfaces of the building:

$$I_o = I_{sc}\left[1 + 0.033\, cos\left(360\ \frac{(nd-3)}{365}\right)\right] \qquad (8)$$

I_o: Extraterrestrial radiant flux

I_{sc}: Solar constant

nd: Day number

$$ET = 2.2918\left[0.0075 + 0.1868\cos\left(360\frac{(nd-1)}{365}\right) - 3.2077\sin\left(360\frac{(nd-1)}{365}\right) - 1.4615\cos\left(2\times 360\frac{(nd-1)}{365}\right) - 4.089\sin\left(2\times 360\frac{(nd-1)}{365}\right)\right] \quad (9)$$

AST=LST+ET/60 + (LON-LSM)/15 (10)

LSM=15 TZ (11)

To calculate solar declination (δ),

$$\delta = 23.45\, sin\left(360\frac{(nd+284)}{365}\right) \quad (12)$$

Sun position equations (SH) are as follows:

$SH = 15\ (AST - 12)$, (SH=0 at noon) (13)

$\beta = \cos LL \cos\delta \cos SH + \sin LL \sin\delta$ (0< β <90) (14)

$\xi = sin^{-1}(\sin SH \cos\delta / cos\beta)$ (15)

The surface-solar azimuth angle γ is defined as the angular difference between the solar azimuth ξ and the surface azimuth Ω. Values of γ greater than 90° or less than –90° indicate that the surface is in the shade:

$$\gamma = \xi - \Omega \quad (16)$$

The clear-sky solar radiation can be estimated as

$$ms_{Air} = \frac{1}{[sin\,\beta + 0.50572(6.07995 + \beta)^{-1.6364}]} \quad (17)$$

$$BNI = I_o exp\left[-\tau_b ms_{Air}^{ab}\right] \quad (18)$$

$$DHI = I_o exp\left[-\tau_b ms_{Air}^{ad}\right] \quad (19)$$

to calculate a clear-sky solar irradiance incident on the receiving surface (Myers, 2013)

$$I_{s,t} = BNI_t + DHI_t + GRC_t \quad (20)$$

$BNI_t = BNI \cos\theta$ (applicable only when $\cos\theta > 0$; otherwise, $BNI_t = 0$) (21)

$$DHI_t = DHI \times VHR \quad (22)$$

$$VHR = max(0.45, 0.55 + 0.437 cos\theta + 0.313\, cos^2\theta) \quad (23)$$

$$GRC_t = (BNI \sin\beta + DHI) GR\, \frac{1 - \cos\Sigma}{2} \quad (24)$$

where GR taken to be 0.2 (ground reflectance),

$$\dot{Q}_S = \sum((BNI_t.BSHGC + (DHI_t + GRC_t).DSHGC)(1 - AF_k).A_{g,k}.g_k.IF.XF) \quad (25)$$

4.1.3.2 Occupancy loads

This load of people can be calculated as following (Ashrae 2013b):

$$Q_{occ.} = No_{occ.}.E_{occ.}.F_{occ.} \quad (26)$$

$No_{occ.}$: Number of persons

$E_{occ.}$: Energy of each person (W)

$F_{occ.}$: non-dimension factor depends of hour of occupancy.

4.1.3.3 Lighting load

The lights have energy to supply as well and its value can be estimated by:

$$Q_l = No_l . E_l . F_l \quad (27)$$

Q_l: Total energy gain from light

No_l: Number of lights

E_l: Energy of light (W)

F_l: Depends on the type of light.

4.1.3.4 Appliances load

Appliances can add some energy to the building as well, and following equation can usually be used to estimate this value:

$$\dot{Q}_{app.} = E_{app} . No_{app} \quad (28)$$

$\dot{Q}_{app.}$: Heat gain from appliance

$E_{app.}$: Heat gain from appliance (according to the type of appliance)

$No_{app.}$: Number of appliances.

4.2 Total energy and exergy demand

After making all of the above calculations, it is now easy to determine the energy demand for the building:

$$\dot{\phi}_{heating} = (\dot{Q}_{trans} + \dot{Q}_v + \dot{Q}_{inf}) - (\dot{Q}_l + \dot{Q}_s + \dot{Q}_{occ} + \dot{Q}_{app}) \quad (29)$$

Note: In summer, the total heat gain will be added to the loss to be the total energy demand that should be released:

$$\dot{\phi}_{cooling} = \left(\dot{Q}_{trans} + \dot{Q}_{v} + \dot{Q}_{inf}\right) + (\dot{Q}_{l} + \dot{Q}_{s} + \dot{Q}_{occ} + \dot{Q}_{app}) \quad (30)$$

The exergy demand for the building can be calculated from the energy demand value according to a simple method of calculating or by using a detailed method (Schmidt, 2009) . According Schmidt, here is good agreement between these two methods, so the simple method will be used in this analysis:

$$\dot{\psi}_{D,heating} = \dot{\phi}_{heating}.\left(1 - \frac{T_0}{T_R}\right) \quad \text{For heating load} \quad (31)$$

$$\dot{\psi}_{D,cooling} = \dot{\phi}_{cooling}.\left(\frac{T_0}{T_R} - 1\right) \quad \text{For cooling load} \quad (32)$$

In this part of calculation, the following assumptions are made:

1- The overall heat transfer coefficient (U) of all the building components are constant;

2- The ambient temperature changes hourly;

3- The internal loads such as lighting, occupancies, and appliances are not considered;

4- The solar gain from the windows is ignored.

By using these two equations, the exergy demands in building can be calculated (walls, roofs, floors, windows, doors, and windows, and door frame (Dincer & Rosen, 2012).

4.3 Heating and Ventilation Systems

The building uses four main parts for conditioning: a centrifugal chiller for cooling, a gas boiler for heating, a distributive pipes network, and 4 pipe fan coils. In this part, we explain the information and mathematical analysis of each part.

4.3.1 Fan coils, AHU and Distributors Analyses

Hot or chilled water is used to cool/heat air in order to condition the building. The hot/cold water is supplied to the building by distributive pipes, as explained in Figure 4.3, that explains the schematic diagram of the hot/cold water stream. After determining the heating energy of the building and its exergy value, the heating system was studied to quantify the energy flow through the components of the system. The first component discussed is the fan coil, which is a water to air heat exchanger. Its energy balance can be written as (Çengel & Boles 2011):

$$\dot{\phi}_{FC,in} = \dot{\phi}_{FC,out} + \dot{\phi}_{FC,loss} \tag{33}$$

$$\dot{\phi}_{FC,out} = \dot{m}_{Air}\left(h_{Air,in} - h_{Air,out}\right) = \dot{\phi}_{h} \tag{34}$$

Therefore, the fan coil energy efficiency is

$$\eta_{e,FC} = \frac{\dot{\phi}_{h}}{\dot{\phi}_{FC,in}} \tag{35}$$

and the input energy of the fan coil can be written as

$$\dot{\phi}_{FC,in} = \frac{\dot{\phi}_{h}}{\eta_{e,FC}} \tag{36}$$

The exergy balance is completed with a similar method to the energy balance with entropy terms, and the corresponding exergy efficiency can be written as follows (Paniagua et al., 2013):

$$\eta_{x,FC} = \frac{\dot{\psi}_{D}}{\dot{\psi}_{FC,in}} \tag{37}$$

Hence, the input exergy to the fan coil is

$$\dot{\psi}_{FC,in} = \frac{\dot{\psi}_{D}}{\eta_{x,FC}}. \tag{38}$$

The main assumptions made for the heating system are:

1- The flow rates of both the water and air are stable and constant.

2- The inlet and outlet temperatures of both water and air are constant.
3- The reference temperature of the fan coil is the ambient temperature, which changes hourly.
4- The ambient temperature is measured continuously by the Ozyegin University weather station.

This procedure can be applied to both heating and cooling states.

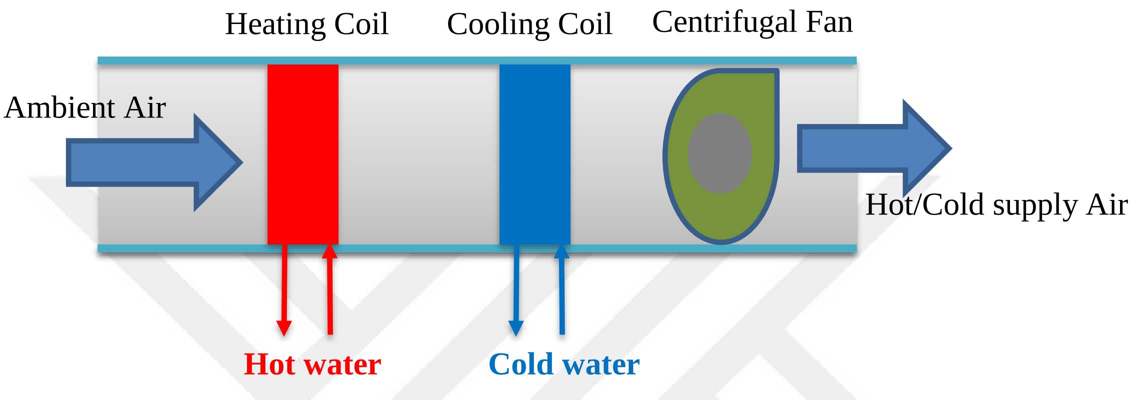


Figure 4. 3 Schematic diagram of 4-pipe fancoil

The distribution pipes (Figure 4.4) can be considered as entrance and exit points representing the input and output energies. So, the losses in pipes are the difference between the input and the output values. Similarly, the destroyed exergy is the difference between exergies at those two points (Bali & Sarac, 2008). The input energy and exergy are expressed as follows (Çengel & Boles, 2011):

Figure 4. 4 Schematic diagram of distributive pipes

Based on energy balance of any open stream, the entrance and exit points of the distribution pipes correspond to the input and output points. Therefore, the losses in the pipes correspond to the difference between the input and the output energies. Similarly, the destroyed exergy is the difference between the exergies at those two points (Bali & Sarac, 2008). The input energy and exergy are expressed as follows (Çengel & Boles 2011):

$$\dot{\phi}_{Dis,in} = \frac{\dot{\phi}_h}{\eta_{e,Dis} \cdot \eta_{e,FC}} = \frac{\dot{\phi}_h}{\eta_{e,Dis} \cdot \eta_{e,FC}} \tag{39}$$

$$\dot{\psi}_{Dis,in} = \frac{\dot{\psi}_{FC,in}}{\eta_{x,Dis}} = \frac{\dot{\psi}_D}{\eta_{x,Dis} \cdot \eta_{x,Fc}} \tag{40}$$

In this part of the heating system, the assumptions made are identical to the assumptions used for the fan coil.

4.3.2 Chiller Analysis

In order to start the mathematical analysis, the centrifugal chiller, which is used only in summer, was considered first, as explained in Figure 4.5 The source of energy in this device is the compressor that consumes electricity as a main input power, and it equals the input power of the compressor; its energy analysis and exergy analysis has been explained in many references such as Dincer & Rosen (2000), Bejan (2002), and Çengel & Boles (2011).

The input power the compressor equals

$$\dot{W}_{comp} = \dot{E}_{elec} = \dot{\phi}_{comp,in} \tag{41}$$

Hence, the compressor is the first part to be analyzed, and its output power equals

$$\dot{\phi}_{comp,out} = \dot{Q}_{comp} = \dot{m}_{cg}(h_2 - h_1) \tag{42}$$

where $\dot{m}_{cg}$: it is the cooling gas of the chiller.

Hence, the energy efficiency of the compressor equals

$$\eta_{e,comp} = \frac{\dot{\phi}_{comp,out}}{\dot{\phi}_{comp,in}} \tag{43}$$

The main exergy equations of the compressor can be abstracted as follow:

exergy destruction in compressor($\dot{\psi}_{dest,comp}$)

$$\dot{\psi}_{dest,comp} = T_0.\dot{S}_{gen,1-2} = \dot{m}.T_0(s_2 - s_1) \tag{44}$$

For the centrifugal chiller, the input energy represents the electricity, and the exergy value of electrical energy equals the electrical energy itself (Boonassa et al., 2006). Hence, it can be calculated as

$$\dot{W}_{x,comp} = \dot{W}_{e,comp} = \dot{\psi}_{comp,in} \tag{45}$$

and the exergy efficiency of the compressor can be calculated as

$$\eta_{x,comp} = 1 - \frac{\dot{\psi}_{dest,comp}}{\dot{W}_{x,comp}} \tag{46}$$

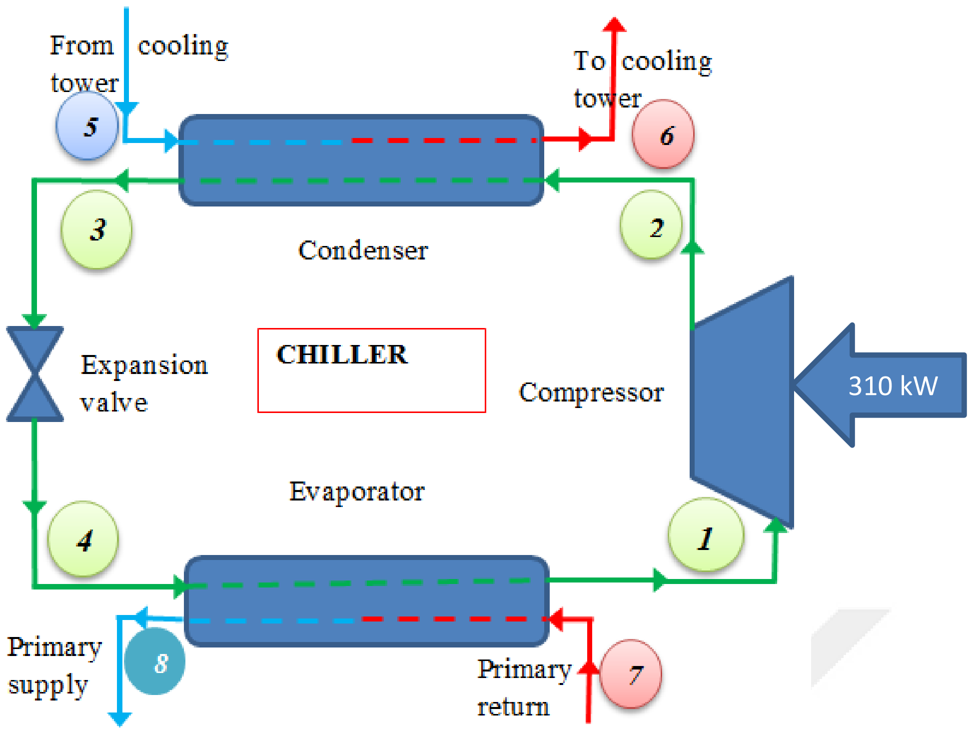


Figure 4. 5 The cycle of the centrifugal chiller in a building

After the compressor, the cooling gas goes to the condenser where the cooling gas is cooled by a cooling tower that uses water as a cooling fluid, and the energy balance in the condenser is

$$\dot{m}_{cg}(h_2 - h_3) = \dot{m}_w(h_6 - h_5) + \dot{Q}_{loss} \quad (47)$$

$$\dot{\phi}_{cond,in} = \dot{m}_{cg}(h_2 - h_3) \quad (48)$$

$$\dot{\phi}_{cond,out} = \dot{m}_w(h_2 - h_3) \quad (49)$$

$$\eta_{e,cond} = \frac{\dot{\phi}_{cond,out}}{\dot{\phi}_{cond,in}} \quad (50)$$

or

$$\eta_{e,cond} = 1 - \frac{\dot{Q}_{loss}}{\dot{\phi}_{cond,in}} \quad (51)$$

It should be noted that there are flow stream and heat transfer processes through the flow stream, so the destroyed exergy within the condenser can be estimated by

$$\dot{\psi}_{dest,cond} = T_0.\dot{S}_{gen,2-3} = T_0[\dot{m}.(s_3 - s_2) + \frac{\dot{Q}_{loss}}{T_H}] \quad (52)$$

where $T_H = \frac{T_5+T_6}{2}$ (53)

Next, exergy at any point in the cycle for flow stream can be written as

$$\dot{\psi}_i = \dot{m}_i[(h_i - h_0) - T_0(s_i - s_0)] \quad (54)$$

hence,

$$\dot{\psi}_{cond,in} = \dot{\psi}_2 - \dot{\psi}_3 \quad (55)$$

$$\dot{\psi}_{cond,out} = \dot{\psi}_6 - \dot{\psi}_5 \quad (56)$$

Finally, the exergy efficiency of the condenser equals

$$\eta_{x,cond} = \frac{\dot{\psi}_{cond,out}}{\dot{\psi}_{cond,in}} \quad (57)$$

The throttle valve is in the next part of the cycle where the enthalpy values are equal. which means that there no energy loss in this part:

$$h_3 = h_4 \quad (58)$$

But, in contrast to energy in the expansion valve, there is exergy destruction in the exergy in this part, and it is equal to

$$\dot{\psi}_{dest,valv} = T_0.\dot{S}_{gen-3-4} = \dot{m}.T_0(s_3 - s_4) \quad (59)$$

$$\dot{\psi}_{valv,in} = \dot{\psi}_3 - \dot{\psi}_4,$$

$$\eta_{e,valve} = 1 - \frac{\dot{\psi}_{dest,valv}}{\dot{\psi}_{valv,in}} \tag{60}$$

An evaporator is not different from a condenser, so the same equations can be applied here:

$$\dot{\psi}_{dest,evap} = T_0.\dot{S}_{gen-4-1} = T_0[\dot{m}.(s_1 - s_4) + \frac{\dot{Q}_L}{T_L}] \tag{61}$$

$$T_L = \frac{T_7+T_8}{2} \tag{62}$$

$$\dot{\psi}_i = \dot{m}_i[(h_i - h_0) - T_0(s_i - s_0)] \tag{63}$$

$$\dot{\psi}_{evap,in} = \dot{\psi}_4 - \dot{\psi}_1 \tag{64}$$

$$\dot{\psi}_{evap,out} = \dot{\psi}_7 - \dot{\psi}_8 \tag{65}$$

$$\eta_{x,evap} = \frac{\dot{\psi}_{evap,out}}{\dot{\psi}_{evap,in}} \tag{66}$$

Equations 17, 18, 19, and 20 are applicable to distributors within the heating or cooling systems.

For the chiller, the COP (coefficient of performance) normally is used instead of energy efficiency, which equals the cooling effect to the input work (Çengel & Boles, 2011). The cooling effect represents the energy absorbed by the chilled water, and the input power represents the compressor input power. So, the COP of chiller equals

$$\dot{\phi}_{CH,in} = \dot{\phi}_{comp,in} = \dot{W}_{comp,in} \tag{67}$$

$$\dot{\phi}_{CH,out} = \dot{\phi}_{evap,out} = \dot{m}_w(h_7 - h_8) \tag{68}$$

$$COP_{CH} = \frac{\dot{\phi}_{CH,out}}{\dot{\phi}_{CH,in}} \tag{69}$$

and the exergy efficiencies of the centrifugal chiller, according to the exergy efficiency of each part, can be written as

$$\eta_{x,CH} = \frac{\dot{\psi}_{evap,out}}{\dot{\psi}_{comp,in}} \tag{70}$$

To make a link between the cooling load and input energy and exergy to the chiller, the following equations can be used (Schmidt, 2009):

$$\dot{\phi}_{CH,in} = \frac{\dot{\phi}_{Dis,in}}{\eta_{e,CH}} = \frac{\dot{\phi}_{h}}{\eta_{e,FC} \cdot \eta_{e,Dis} \cdot COP_{CH}} \tag{71}$$

while the exergy input can be written as

$$\dot{\psi}_{CH,in} = \frac{\dot{\psi}_{Dis,in}}{\eta_{x,CH}} = \frac{\dot{\psi}_{D}}{\eta_{x,Fc} \cdot \eta_{x,Dis} \cdot \eta_{x,CH}} \tag{72}$$

4.3.3 Boiler Analysis

For the heating load, the boiler that uses natural gas as fuel is used to produce the hot water that is distributed to the buildings and heats them, as explained in Figure 3.3. The schematic diagram of the boiler, inlet, and outlet can be seen in Figure 4.6.

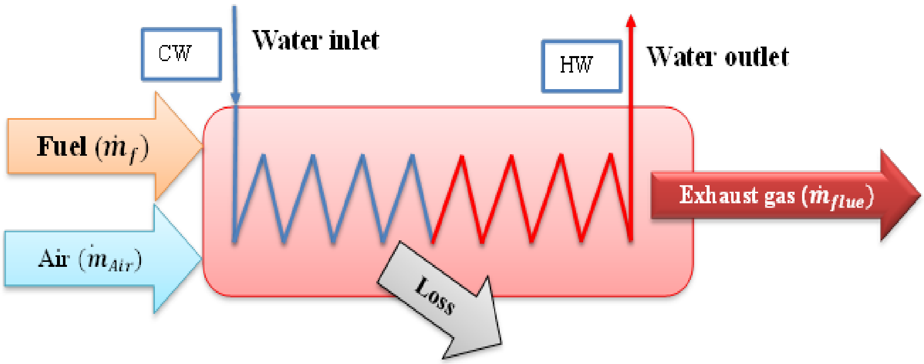


Figure 4. 6 Schematic diagram of inlet and outlet energies of a boiler

The energy balance of the boiler can be expressed as

$$\dot{\phi}_{B,in} = \dot{\phi}_{B,out} + \dot{\phi}_{B,loss} \tag{73}$$

$$\dot{\phi}_{B,in} + \dot{m}_{Air}.h_{Air} + \dot{m}_{W}.h_{CW} = \dot{m}_{flue}.h_{flue} + \dot{m}_{w}.h_{Hw} + \dot{\phi}_{B,loss} \tag{74}$$

As seen in Figure 2, the useful output energy represents the energy that is added to the water stream and the input power to the boiler; this equals the fuel energy while the energy of inlet air is not considered. By considering flue (exhaust) gas energy as a part of the losses, the energy efficiency of the boiler can be written as follows (Compton & Rezaie, 2017):

$$\eta_{e,B} = \frac{\dot{m}_{w}.(h_{HW} - h_{CW})}{\phi_{B,in}} \tag{75}$$

The output energy of the boiler equals the input energy to the distributor; therefore, the input energy to the boiler becomes (Compton & Rezaie, 2017)

$$\dot{\phi}_{B,in} = \frac{\dot{\phi}_{Dis,in}}{\eta_{e,B}} = \frac{\dot{\phi}_{h}}{\eta_{e,FC}.\eta_{e,Dis}.\eta_{e,B}} \tag{76}$$

The exergy balance of the boiler does not differ from the energy balance and written as

$$\dot{\psi}_{B,in} = \frac{\dot{\psi}_{Dis,in}}{\eta_{x,B}} = \frac{\dot{\psi}_{D}}{\eta_{x,Fc}.\eta_{x,Dis}.\eta_{x,B}} \tag{77}$$

The assumptions for the boiler calculations are as follows:

1- The flow rates for input fuel and water of the boiler are constant and stable.

2- The temperatures of inlet and outlet hot water are constant.

3- The exergy factor of natural gas is considered to be 0.9 (Schmidt, 2004a).

4- The ambient temperature changes hourly.

5- The energy and exergy of air are not considered.

In addition to the heating load energy, we add lighting, ventilating, and domestic hot water (DHW) energies to the heat-energy demand. The components of the heating system need auxiliary electrical energy to be turned on,

$$ED = \dot{\phi}_{B,in}.F_P + \left(P_l + P_{ve} + P_{aux,B} + P_{aux,Dis} + P_{aux,FC}\right).F_{P,elec.} + \dot{\phi}_{DHW}.F_{P,DHW}$$

(78)

and the total exergy demand becomes

$$XD = \dot{\phi}_{B,in}.F_P.F_q + \left(P_l + P_{ve} + P_{aux,B} + P_{aux,Dis} + P_{aux,FC}\right).F_{P,elec.}.F_{q,elec.} + \dot{\phi}_{DHW}.F_{P,DHW}.F_{q,DHW} \quad (79)$$

$F_P, F_{P,DHW}, F_{P,elec}, F_q, F_{q,DHW}, and\ F_{q,elec}$ values are were taken to be 1.1, 1.1, 3, 0.9, 0.9, and 1, respectively, as suggested by Schmidt (2004a).

Note that $F_P = F_{P,DHW}$, and $F_q = F_{q,DHW}$ because there is one boiler which is used simultaneously for the heating and domestic hot water.

4.3.4 Tri-generation System Analysis

As the name suggests, tri-generation provides a third form of energy cooling energy in addition to heat and power. Tri-generation systems, also called combined cooling, heating, and power (CCHP) systems, are typically a combination of cogeneration plants and chillers to produce electricity, heat, and cooling energy in one process. A tri-generation system uses only one source of primary energy while providing power, all these three energies simultaneously. This primary source can be represented by either fossil fuels, or natural gas (the present tri-generator) or some appropriate renewable energy sources (biomass, biogas, solar energy, etc.) (Sibilio et al., 2017). Figure 4.7 depicts a simple diagram of a tri-generation system that is usually used in buildings. The tri-generation system has two modes. The first is heating, which is applied in winter season. In this mode, the absorption chiller is not used, so the total hot water that is produced by the boiler is used for heating and DHW purposes. Moreover, Table 4.1 includes more information about the energy that the tri-generator produces. In addition, a sample of experimental data can be seen in Figure 4.8. In addition, Appendix A shows how these data collected in addition to some samples.

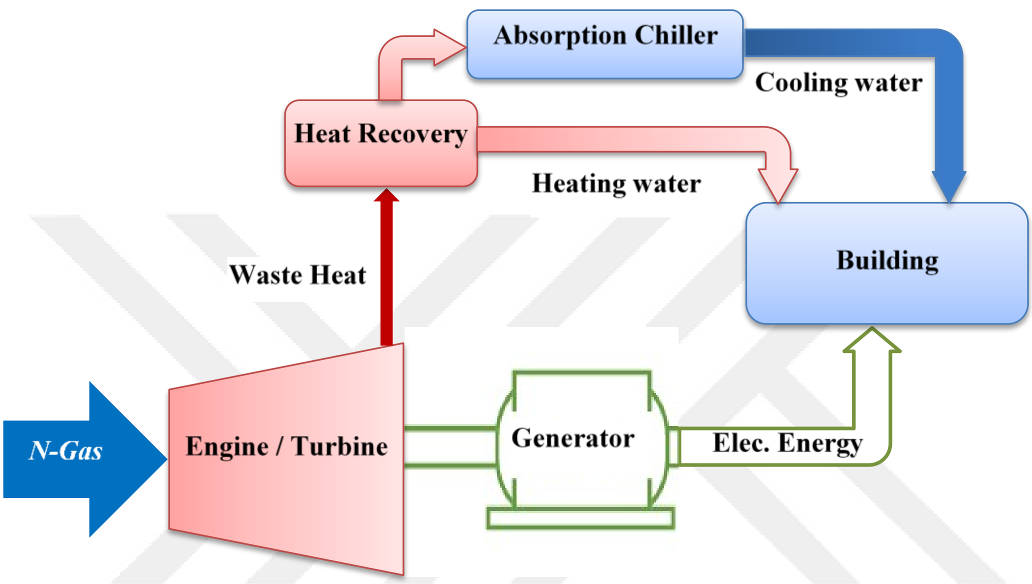


Figure 4. 7 The tri-generation system diagram general mode.

Table 4. 1 Tri-generation system information

Fuel Type	Natural gas
Fuel consumption (kW)	3,620 kW, (335 m^3/h)
Exhaust gas flow rate (kg/h)	8,574
Electrical eff.%	43%
Thermal eff. %	44%
Chilled water flowrate (m^3/h)	267
Cooling tower water flowrate (m^3/h)	460
Hot water flowrate (to chiller) (m^3/h)	29
Cooling capacity (kW)	1,560 kW
Heating capacity (kW)	840 (Boiler), 720 (chiller)
Tri-generator investment cost USD	1,053,453 USD
Hot water temperatures in/out (^{o}C)	90/70
Chilled water temperatures in/out (^{o}C)	7/13

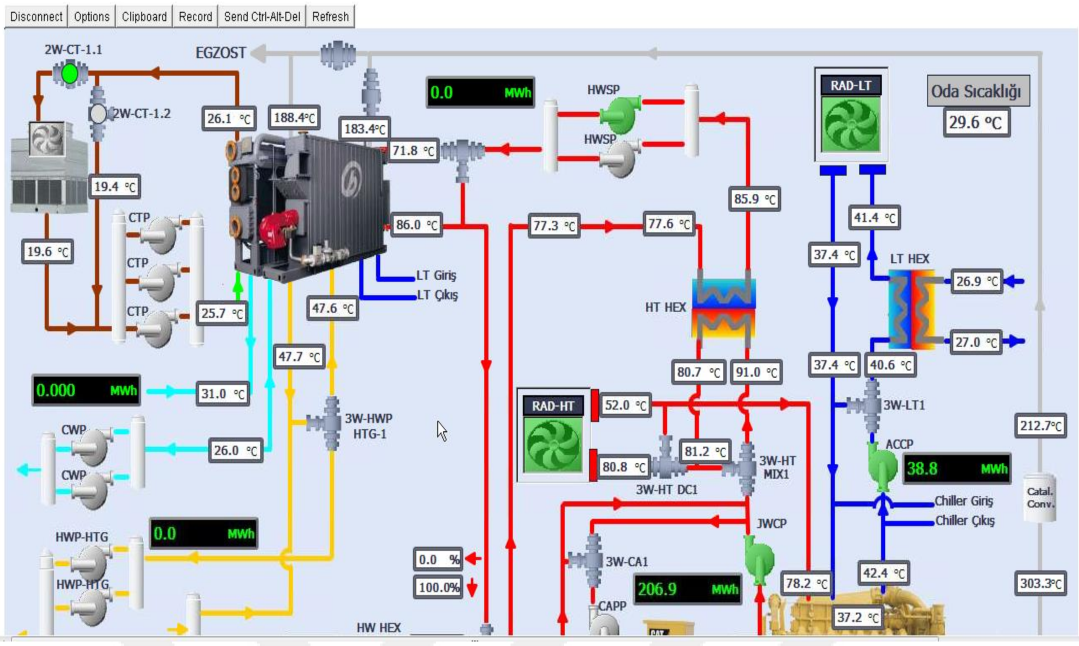


Figure 4. 8 The tri-generation system experimental data

4.3.4.1 Heating Mode

Figure 4.9 shows the energy and exergy balances of the tri-generator for both modes, heating and cooling. In the heating mode, the energy and exergy efficiency of the Tri-generator can be quantify as follows (Ahmadi et al., 2011; Mahmoudi & Kordlar, 2018; Al Moussawi et al., 2016):

$$\eta_{e,Tri} = \frac{\dot{\phi}_{Tri,elec}+\dot{\phi}_{Tri,heating}}{\dot{\phi}_{Tri,in}} \quad (80)$$

Where

$$\dot{\phi}_{Tri,in} = \dot{\phi}_{fuel}$$

$\dot{\phi}_{fuel}$: Tri-generator input energy (Fuel energy).

From equation 80 by knowing the electricity and heating energy demands and Tri-generator efficiency the input energy (Fuel energy) can be estimated from the same equation as:

$$\dot{\phi}_{Tri,in} = \frac{\dot{\phi}_{Tri,elec}+\dot{\phi}_{Tri,heating}}{\eta_{e,Tri}} \quad (81)$$

Similarly, from the exergy balance of the tri-generator the exergy efficiency equals:

$$\eta_{x,Tri} = \frac{\dot{\psi}_{Tri,elec}+\dot{\psi}_{Heating}}{\dot{\psi}_{Tri,in}} \quad (82)$$

For input exergy demand can be determined by the same way

$$\dot{\psi}_{Tri,in} = \frac{\dot{\psi}_{Tri,elec}+\dot{\psi}_{Heating}}{\eta_{x,Tri}} \quad (83)$$

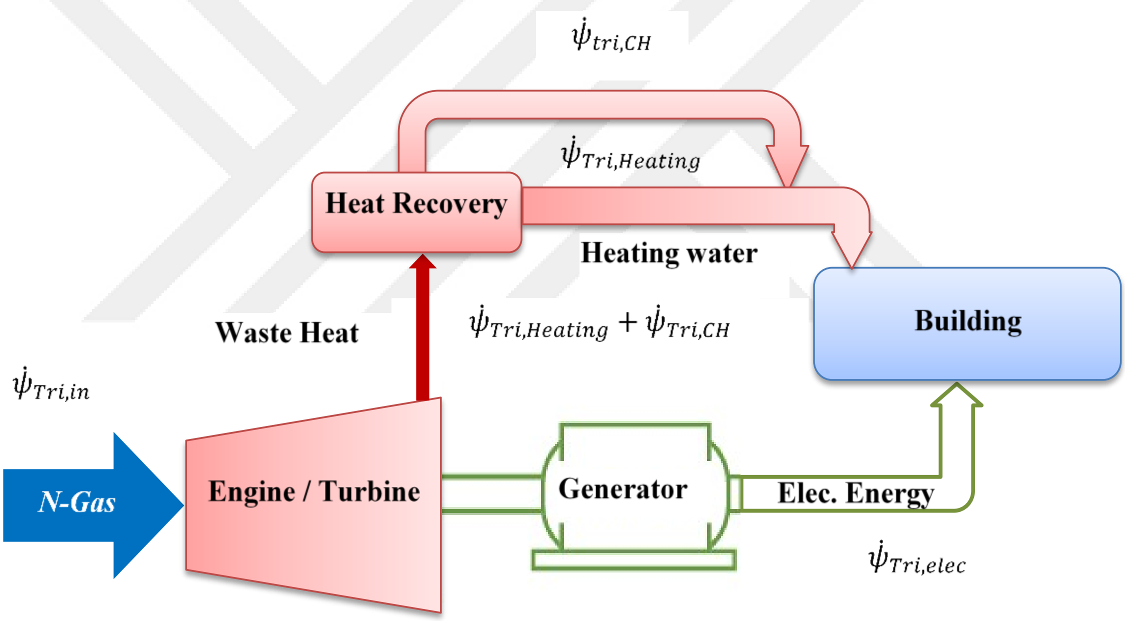


Figure 4. 9 The tri-generation system diagram general mode.

4.3.4.2 Cooling Mode

The cooling mode can be seen in Figure 4.9 as well. In this case, three types of energy are produced: electricity, hot water, and chilled water. Electricity is produced by the generator, the hot water is produced by the recovery system, and the absorption chiller, which works by hot water, produces the chilled water, which is considered last type of energy. Hence, the energy and exergy balance of this mode can be written as follows (Mahmoudi & Kordlar, 2018):

$$\eta_{e,Tri} = \frac{\dot{\phi}_{Tri,elec}+\dot{\phi}_{Tri,heating}+\dot{\phi}_{Tri,CH}}{\dot{\phi}_{Tri,in}} \quad (84)$$

From equation 45, by knowing the electricity and heating energy demands and the tri-generator efficiency, the input energy (fuel energy) can be estimated from the same equation as follows:

$$\dot{\phi}_{Tri,in} = \frac{\dot{\phi}_{Tri,elec}+\dot{\phi}_{Tri,heating}+\dot{\phi}_{Tri,CH}}{\eta_{e,Tri}} \quad (85)$$

The exergy balance does not differ from the energy balance, so the input exergy can be estimated as

$$\eta_{x,Tri} = \frac{\dot{\psi}_{Tri,elec}+\dot{\psi}_{Heating}+\dot{\psi}_{Tri,CH}}{\dot{\psi}_{Tri,in}} \quad (86)$$

For input exergy, the demand can be determined in the same way:

$$\dot{\psi}_{Tri,in} = \frac{\dot{\psi}_{Tri,elec}+\dot{\psi}_{Heating}+\dot{\psi}_{Tri,CH}}{\eta_{x,Tri}} \quad (87)$$

4.4 Exergoeconomic Analysis

The cost of any part includes many aspects including purchase, installation, and operation, maintenance. In addition. the cost of electricity is considered the most important factor that affecting the overall cost. According to the theory presented in Tsatsaronis & Morosuk (2012) and Cassetti et al. (2013), the exergoeconomic balance equation (Figure 4.10) for each component of the cycle can be written as follows(Tsatsaronis and Morosuk 2012, Cassetti *et al* 2013):

$$\dot{cost}_{in} + \dot{Z}_j = \dot{cost}_{out} \tag{88}$$

where $\dot{cost}_{in}$ and $\dot{cost}_{out}$ represent the costs of entering and exiting the streams, respectively. $\dot{Z}_j$ symbolizes the capital, operating, and maintenance costs, and it can be estimated based on the following formula (Yücer & Hepbasli, 2014):

$$\dot{Z}_j = \frac{Cost_{inv}.CRF.\lambda}{NH.3600} \tag{89}$$

where $Cost_{inv}$ represents the capital cost, and *CRF*, which is the capital recovery factor, can be calculated by

$$CRF = \frac{i.(1+i)^{ny}}{(1+i)^{ny}-1} \tag{90}$$

where *i* is the interest rate, and *ny* is the operating period in years.

Lastly, the relation between the cost and exergy of any equipment within the system can be done based on the exergetic cost coefficient (c_i), which represents the cost per unit of exergy ($/kWh) as written in following equation:

$$\dot{cost}_{j,in} = c_{j,input}.\dot{\psi}_{j,in} \tag{91}$$

$$\dot{cost}_{j,out} = c_{j,product}.\dot{\psi}_{j,out} \tag{92}$$

where(c_i): specific cost ($/kWh).

Note that the exergetic cost coefficient at the exit of any of the component equals the exergetic cost coefficient at the inlet of the next component.

By applying these equations, the cost of exergy output from each part will be known. and the cost of the exergy demand of building will be known as well, so it is time to start using building exergy analysis.

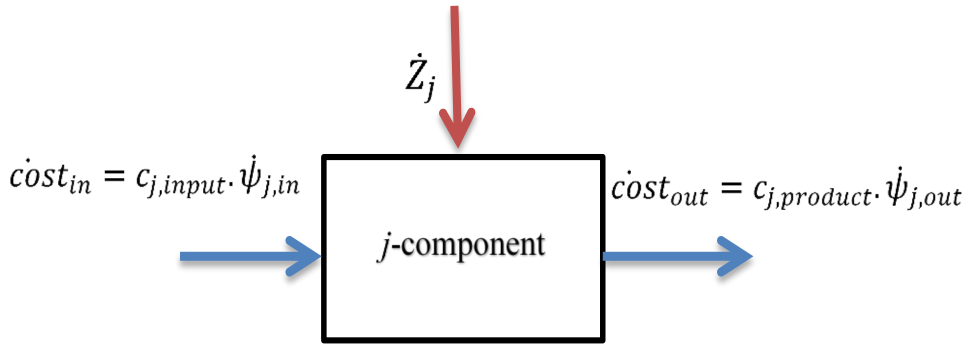


Figure 4. 10 The schematic to show the basic concepts of exergoeconomic analysis (adapted from Yücer & Hepbasli, 2014)

(*j*- component can be chiller, boiler, tri-generator, distributor, and fan coil).

An exclusive figure is required to makes the image clearer, so enviro-economic analysis might contribute to that. Emission is another negative impact of the increasing energy consumption that leads to climate change. The formula by Caliskan et al. (Caliskan *et al* 2012) can be used to estimate the amount of CO_2 emissions that are produced from any energy productive machine:

$$Y_{CO2} = AN_{CO2}.WY_P.NH \tag{93}$$

Where Y_{CO2} represents the CO_2, emission produced in a year (tCO2/year), AN_{CO2} is the CO_2 emission during the fuel (natural gas) firing process (0.19 $kgCO_2/kWh$) (Cervigni *et al* 2013, Greenhouse Gas Reporting Program (GHGRP) 2017), WY_p is the annual power that is produced by using annual consumption (Y_{CO2}) of fuel, and *NH* is the annular operating time in hours (Yucer & Hepbasli, 2013).

The price of natural gas is assumed to be 0.0242 $/kWh (Bagdanavicius et al., 2012), the international price of carbon is assumed to be 28 $/tCO_2$,(Kossoy & Peszko, 2015), and the price of electricity is assumed to be 0.072 $/kWh (Turkish Statistical Institute, 2017; Al-Alfi, 2018).

Completing the analyses of each component of the building and its conditioning system means that the calculation steps of the energy, exergy, exergoeconomic analyses can be started. The analyses sequences are abstracted in Figure 4.11 which explains the main steps of the analyses.

From the figure, it can be seen that all the energy and exergy analyses were based on the heating load of the building and the efficiencies of the conditioning system components which lead to estimating the energy and exergy input to the boiler. In addition to the boiler input energy and exergy, the lighting, ventilating, and domestic hot water (DHW) energies should be added to quantify the total energy demand. By adding all of them, the total energy and exergy demands can be determined as

$$ED = \phi_{B,in}.F_P + \left(P_l + P_{ve} + P_{aux,B} + P_{aux,Dis} + P_{aux,FC}\right).F_{P,elec.} + \phi_{DHW}.F_{P,DHW} \quad (94)$$

and the total exergy demand becomes

$$XD = \phi_{B,in}.F_P.F_q + \left(P_l + P_{ve} + P_{aux,B} + P_{aux,Dis} + P_{aux,FC}\right).F_{P,elec.}.F_{q,elec.} + \phi_{DHW}.F_{P,DHW}.F_{q,DHW} \quad (95)$$

$F_P, F_{P,DHW}, F_{P,elec}, F_q, F_{q,DHW}, and\ F_{q,elec}$ values were taken to be 1.1, 1.1, 3, 0.9, 0.9, and 1, respectively, as suggested in Schmidt (2004a). $F_P = F_{P,DHW}, and\ F_q = F_{q,DHW}$ because there is a single boiler producing the heating and domestic hot water simultaneously.

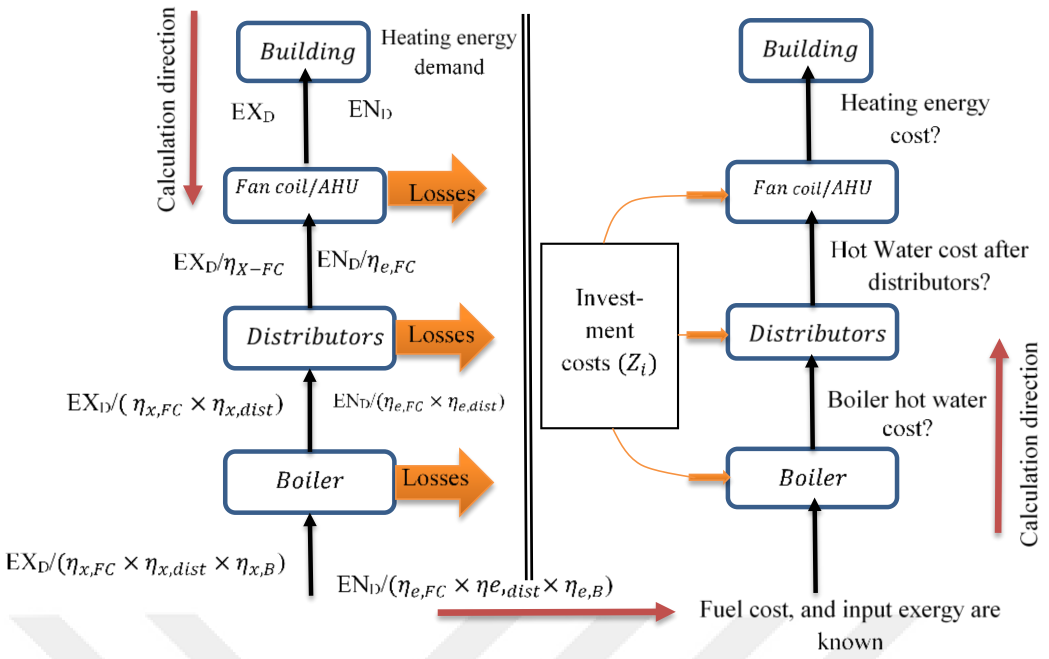


Figure 4. 11 Schematic diagram explaining the calculation steps for energy, exergy, and cost.

4.5 MACC Analysis

There are two types of approaches that are applied to estimate the Marginal Abatement Cost Curve (MACC) curve: static and dynamic. The static approach considers all GHG mitigation technologies/options are compared assuming as if they are implemented now, and all emissions reductions can be realized immediately. However, in reality, recognition of GHG alleviation possibility of a technology/option happens over time. Hence, adopting the dynamic analysis achieves more accuracy results relative to static analysis, because the efficiencies of the devices change over time (Kesicki and Ekins 2012, Tomaschek 2015).

The dynamic MAC can be estimated as follows:

$$MAC = \frac{AC^M - AC^B}{EM^B - EM^M} \tag{96}$$

where *AC* and *EM* refers to discounted total costs and total emissions, superscripts *M* and *B* refers to GHG mitigation and baseline scenarios. It can be remarked in Eq. (96) that the cost of new scenario can be negative if it reduces the cost whereas, the emission value of any new scenario is positive. These two values of cost and emission (AC and EM) were estimated based on exergy, exergoeconomic, and environmental analyses as they were explained in a previous section of the analysis for the improving processes (mitigation) and baseline (Case 1).

In this part of calculation, a developed MACC is used to estimate the CO_2 and cost savings of improving processes relative to the original case (scenario 1). The detailed method of MACC calculation methodology can be seen in the references (Timilsina et al, 2017; Ibrahim & Kennedy, 2016). In this developed MACC, we connect the CO_2 reduction to the application of improving process with the total cost reduction due to applying the same process. That means that the applied improving processes caused the carbon dioxide reduction, but the cost reduction does not represent only the cost reduction due to CO_2 reduction; it actually represents cost reduction due to energy and carbon dioxide reductions simultaneously. Hence, the X-axis is the total carbon dioxide reduction due to applying the specific process relative to the original case (Case 1) as Fabian (2011) expected researchers to do, whereas the Y-axis represents the total cost reduction that is produced by also applying the specific process relative to the original case. Based on this explanation, the carbon dioxide and cost reduction of any case can be estimated simply as follows:

CHAPTER V
RESULTS AND DISCUSSION

5.1 *Static and Dynamic Analyses*

A pre-design tool, ECBCS Annex 49 (Schmidt, 2009), was used to estimate the energy and exergy demand of the SCOLA Building. Annex 49 is a task-shared international research project within the framework of the International Energy Agency (IEA) program on energy conservation in building and community systems. Its objectives are the creation of the development, assessment and analysis methodologies that lead to reduction of the exergy demand of the building and consequently CO_2 emissions. Moreover, it focuses on the development of exergy distribution and generation and storage systems (Schmidt & Ala-Juusela 2004; Schmidt, 2009; Torio & Schmidt, 2011).

The calculations were performed both in statistical and dynamical fashion. In the static analysis, the reference temperature was considered to be -1°C whereas the building temperature for both analyses was 23°C. The detailed data for temperature used when conducting the dynamic analysis was for the heating season. Furthermore, the contributions of the building components were also estimated. The energy and exergy efficiencies of the heating system were calculated based on energy and exergy balances of each component for both the static and dynamic analyses. The measured and design data of the system were provided by the Ozyegin University Energy Distribution Center (EDS).

The economic analysis of the building was conducted by applying the exergoeconomic analysis in both static and dynamic fashions. This analysis allowed us to calculate the cost of the energy consumed by the building. In addition, this analysis is a useful tool for evaluating the cost of any improvements in the thermal performance of the building. As mentioned before, the enviro economic impact is considered as determining the cost of CO_2 emissions due to the building's energy consumption.

5.1.1 Static Analysis Results

Figure 5.1 represents the results of the static analysis, where the energy and exergy rates for heating the building were found to be 444 and 36 kW, respectively. The transmission and ventilation heat loss rates were calculated to be 241 kW and 203 kW, respectively. The high contribution of ventilation load to energy demand highlights the necessity for further investigation. The contribution of the windows is the second highest load, equivalent to 89 kW, whereas the loss from the walls is 55 kW. The roof also makes a significant contribution to both energy and exergy demands. The contributions of the other components are listed in Figure 5.1.

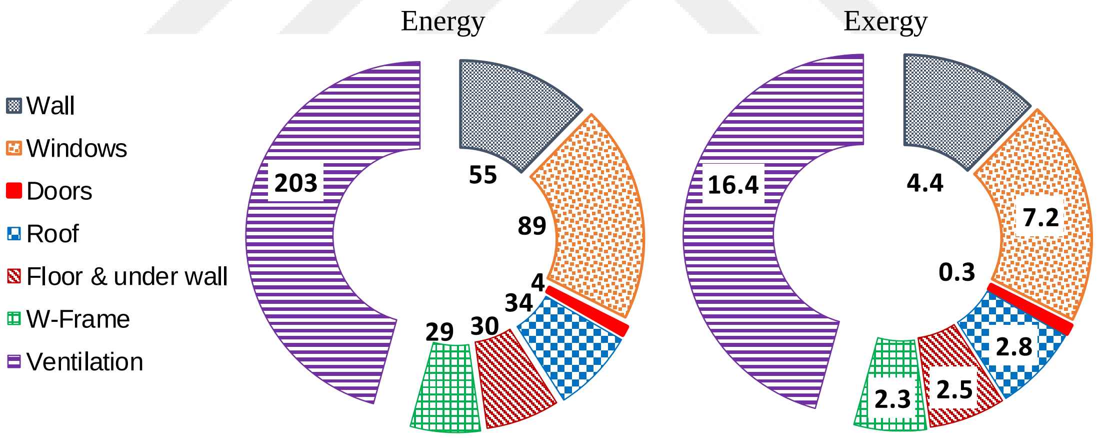


Figure 5. 1 The contributions of the building components in static energy and exergy analyses.

Determining the energy and exergy rates for heating demand is the first step in performing the exergetic analysis of the heating system. For this, the flow of energy and exergy through all components of the heating system should be considered. The results are depicted in Figure 5.2. The input energy and exergy rates to the system are 1.38 MW and 1.34 MW, respectively. There is a reduction in both energy and exergy rates through the system components until they reach the envelope. These reductions occur because of the losses in the components of the heating system until the energy reaches from the source to the building. The energy and exergy rates for heating the building were 444 kW and 36 kW, respectively. The energy and exergy efficiencies for the boiler were found to be 67% and 35%, respectively while their values in the distribution network were 74% and 49%. The difference between energy and exergy flow through the components explains the importance of exergy analysis, which has a clearer decline due to each component. Note that the exergy efficiencies low values for the heating system reveal the necessity of developing their performance to reduce exergy loss and exergy demand. These efficiencies need to be considered when a building is being designed.

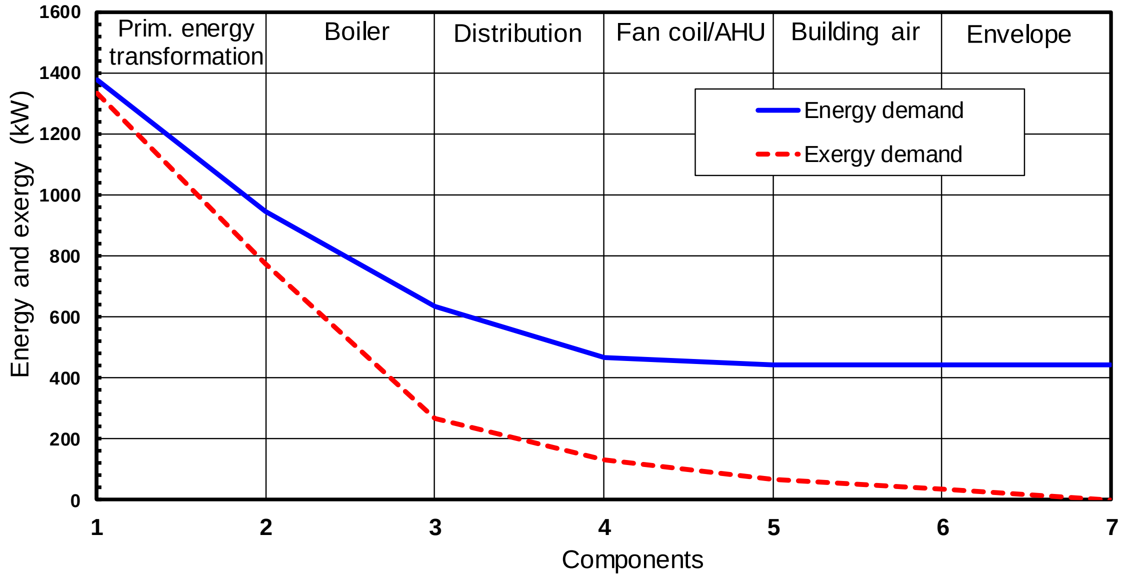


Figure 5. 2 Energy and exergy flow through the heating system components.

Figure 5.3 depicts the energy and exergy losses for all components from the source to the envelope of the building. Examining these losses in static and dynamic fashion would provide a clear understanding of the amount and the source of the losses. Knowing these losses and the components help designers and researchers to choose specific components at the design phase. Based on the results, the highest energy and exergy losses occured in the boiler, with 700 kW and 513 kW, whereas the primary energy transformation had the second highest losses, with 579 and 451 kW, respectively. The losses at the distribution and fan coils are lower. The results explain that developing boiler performance can achieve better results than enhancing the other components because of the high value of the corresponding loss. All these losses and exergy values through the system and components are redrawn in Figure 5.4 by the Sankey diagram to make them clearer.

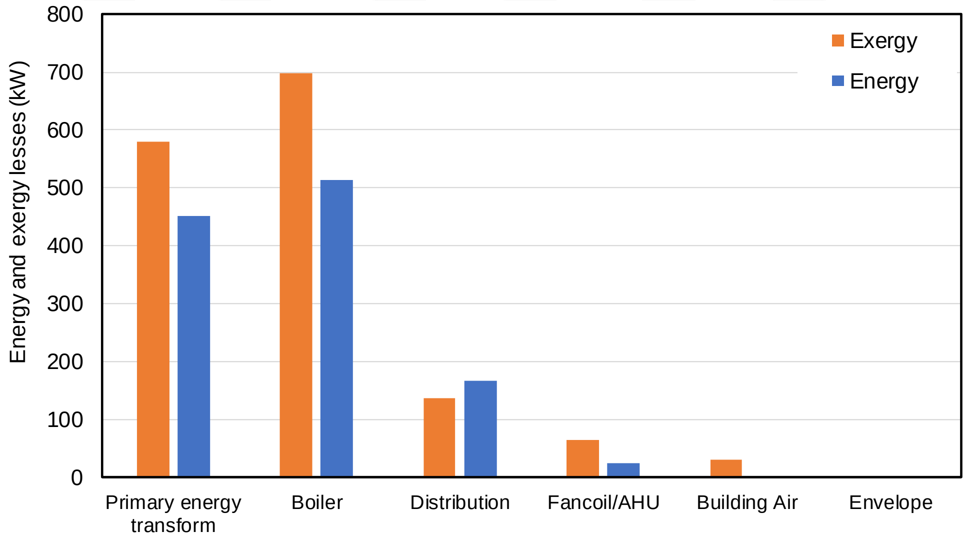


Figure 5. 3 Energy and exergy losses of system components of the SCOLA Building during a one-year period (2016)

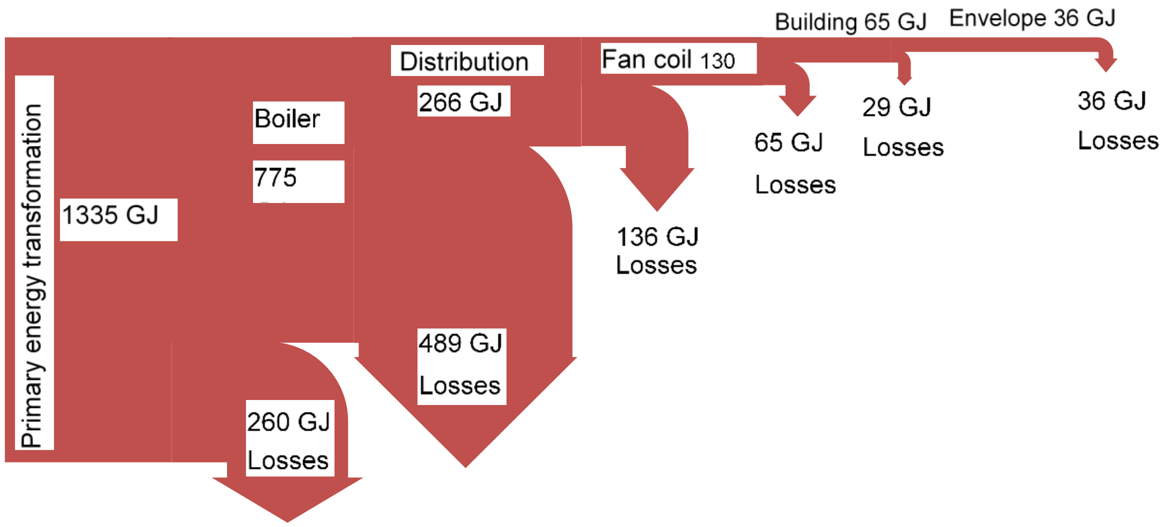


Figure 5. 4 The Sankey diagram of the exergy flow and its losses for the SCOLA Building on the Ozyegin University Campus.

The impact of each component on the losses in the system can be analyzed using the exergy analyses in a tandem way, and new design strategies can be proposed. For instance, if the current boiler is replaced with another one that produces the same amount of energy and has the same energy efficiency, and if it works at a lower temperature range (80/60° C instead of 90/70° C), the energy performance of the building would be the same. Yet, based on the exergy analysis, the exergy losses for an alternative boiler would be less, so the building performance would be improved, and the environmental impact would decrease. Consideration of the energy analysis alone would not help in detecting this difference between the two boilers. A similar analysis can be used for the distribution pipes and fan coils. In short, the real improvements in the building performance can be demonstrated using the exergy analysis.

Completing the exergy analysis and quantifying the exergy values through the building components and their losses represent the starting point for the exergoeconomic analysis. The specific exergy cost (SPECO) method is applied to the heating system components. The SPECO is one of those method used to perform exergoeconomic analysis by applying the cost balance to exergy streams to determine the product cost. In addition to input and output exergies in any stream, the capital investment cost (USD/h) of the *k'th* component should be added to the exergy of the input stream. In this approach, the cost is estimated based on the exergy value because exergy measures the true value of both the first and the second laws of thermodynamics. Using this approach, we next analyze the SCOLA Building.

The investment coefficients and exegetic cost coefficients of the building components are listed in Table 5.1. This table gives further details in addition to the Sankey diagram shown in Figure 5.5 that depicts how the exegetic cost coefficients change throughout the system of the building. Together, they provide a view of the energy cost through the building components by furnishing the exergetic cost coefficients. The highest exergetic cost coefficient was found to be those of the fan coils. The cost coefficient increases from the boiler stage to the fan coils because a specific amount of energy is added to the cost after it passes through the components. Here, $c_{B,product}$ presents the cost in USD of one GJ of produced exergy from the boiler. Simultaneously, $c_{Dis,product}$ and $c_{FC,product}$ present the cost of produced exergy in USD from each of them for one GJ of exergy. Determining those coefficients allows the researchers to estimate the energy consumption cost of the building.

Table 5. 1 Exergoeconomic analysis of the building

Component	Entering exergetic cost	Hourly investment	Exiting exergetic cost
Boiler	$c_{B,input}$	$\dot{Z}_B$ (Boiler)	$c_{B,product}$
	13	3.1	68.5
Distribution	$c_{Dis,input}$	$\dot{Z}_{Dis}$ (Distribution)	$c_{Dis,product}$
	68.5	0.5	141
Fan coil	$c_{FC,input}$	$\dot{Z}_{FC}$ (Fan coil)	$c_{FC,product}$
	141	2.9	292.6

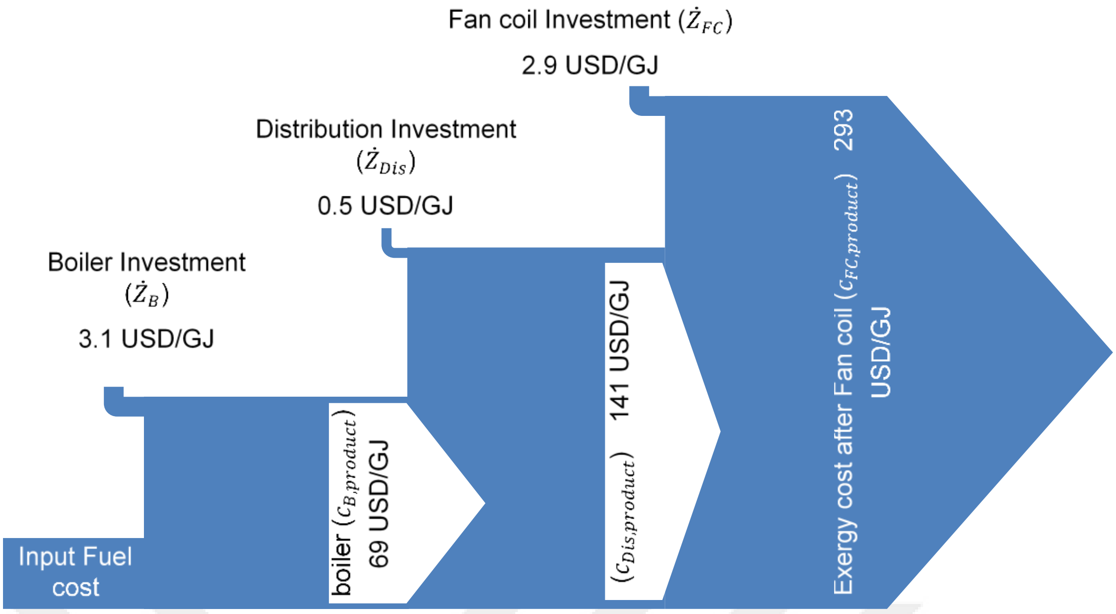


Figure 5. 5. The schematic diagram of exergoeconomic results based on static analysis.

In order to make our discussion clearer, we provide a comparison table of this study and a previous one (Yücer & Hepbasli, 2014). Table 3 shows the main differences between the two buildings that were investigated. Since the available data by Yücer & Hepbasli is static, we give the comparison only for the static analysis. From these comparisons, it can be noticed that for the main differences between the investigated buildings, there is no available data except for this one. The floor area of the SCOLA Building is larger. Also, the indoor unit of SCOLA is a fan coil whereas a panel radiator is used in the other building. Moreover, SCOLA is used for academic purposes while the other building is for residential purposes (dormitory).

First, we compare the heating load of both buildings per meter square of floor area. The heating load of SCOLA is 25 W/m^2 whereas its value in the other building is 81 W/m^2. The large difference favors the SCOLA Building because it has been designed to be one of the low energy buildings. Table 3 also shows the energy and exergy demands of both buildings. The exergy cost coefficient is shown in Table 3 for the fan coil (SCOLA), which is more expensive than the panel radiator (dormitory building). The lower exergy efficiency of the fan coil and higher investment cost cause this difference between these two entries which is against the SCOLA case. However, the total cost of energy consumption in SCOLA is still lower because the energy demand of SCOLA is lower than that of the dormitory building.

Table 5. 2 The main details and the comparison results of the present study for SCOLA and a reference building (Yücer & Hepbasli, 2014).

Building characteristics		
Building type	Academic	Residential (dormitory)
Type of analysis	Static/dynamic	Static
Total area (m^2)	17756	650
Indoor temperature (°C)	23	21
Outdoor temperature (°C)	-1	0
Heating load (W/m^2)	25	81
Energy demand (W/m^2)	80	175
Exergy demand (W/m^2)	77	165
Boiler type	Natural gas boiler	Fuel oil boiler
Distributors	Distribution pipes	Distribution pipes
Indoor unit type	4-pipes fan coil	Panel radiators (emission)
Exergy cost after the boiler ($c_{B,product}$) (USD/GJ)	67	175
Exergy cost after the distributors ($c_{Dis,product}$) (USD/GJ)	141	239
Exergy cost after fan coil or emission ($c_{FC,product}$)/ ($c_{e,product}$) (USD/GJ)	293	257

Note that the overall energy density of SCOLA is measured as 50 W/m^2/year, which makes it one of the most energy efficient academic buildings in Turkey. However, the analysis here does not consider any improvements that have been made for SCOLA, including the earth tube, the internal load automation, the PV cells, and the lighting control systems. Also, the investigation here is only for the heating season; we did not consider the summer months when the energy demand is very low. Hence, the SCOLA value shown in Table 3 is 80 W/m^2/year.

5.1.2 Dynamic Analysis

To achieve more robust predictions for the building performance, a dynamic analysis of the building would be desirable for the entire heating season. Such an analysis was conducted for SCOLA using the hourly change in heating load over the heating season as shown in Figure 5.6. The cooling load was not considered in this calculation; therefore, there was no load shown for the summer period. We note the effect of the reference temperature (ambient temperature) on heating loads during the heating season. The maximum load was found to be for January because the temperatures during this month were the lowest compared to others; the minimum calculated load was in September. Moreover, the figure provides the change of the load during the working hours of any day of any month. The calculations were done only for the working hours. It is clear that such a dynamic analysis provides a comprehensive view of the temporal variations of the load.

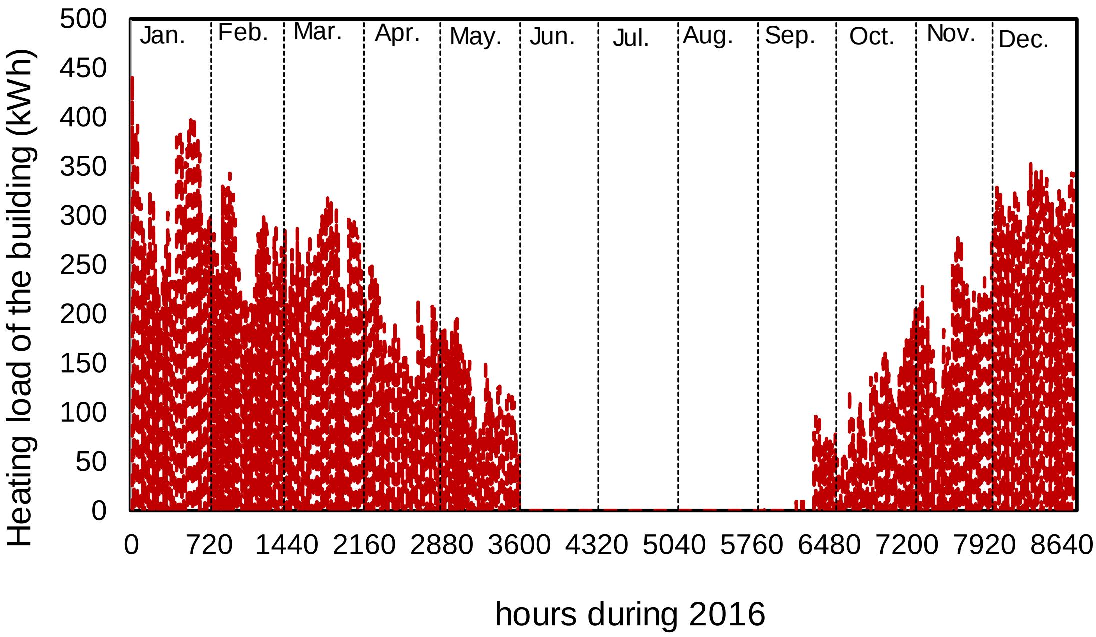


Figure 5. 6. Hourly heating load of the building for the entire year with the details given for the heating season only.

Based on the dynamic analysis, the energy and exergy demands were calculated hourly for the 21st of January; this exercise was just to understand the changes happening during working hours. Figure 5.7 shows how the change of temperature during a day reduces the energy and exergy demands, which follow each other. The reduction occurs because of the decrease in the difference between the room and reference temperatures, which results in a reduction in the energy and the exergy demands. Their values decreased during daytime, and the maximum reduction was 4% at 14:00. This change shows the necessity for carrying out a dynamic analysis for the building.

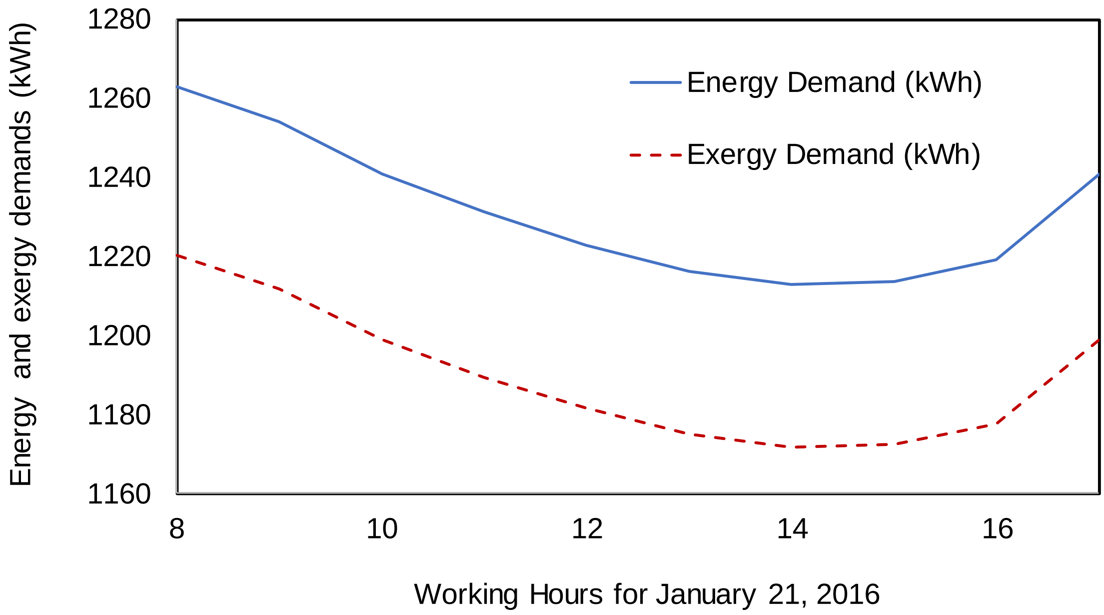


Figure 5. 7 The energy and exergy demand vs. working hours of the SCOLA Building on January 21, 2016.

In contrast to the energy and exergy demands, the exergy deficiency increases during the daytime because of the rise of the reference temperature. Figure 5.8 shows the exergy deficiency changes for the boiler, distribution pipes, and fan coils. The changes are low because they depend on the ambient temperature changes. The ambient temperature changed little during the day on 21st of January; however, the daily change may be larger on other days in Istanbul. On the other hand, the exergy losses of the components decreased instead of increasing shown in Figure 5.9; this contrast occurs because the reductions of energy and exergy demands during a given day are larger than the rise in their values, which is due to the deficiencies of the heating system components. As a result, the energy and exergy losses decrease instead of the opposite. In other words, an increasing reference temperature during a day reduces the energy and exergy demands, whereas the heating system components losses increase due to that rise. These changes are not equal to each other because the increase in energy and exergy losses es less than the reduction of energy and exergy demands.

The hourly changes in the cost and the CO_2 emission are presented in Figure 5.10 for the 21st of January 2016. These values depend on the exergy demand. Their values are functions of the reference temperature, so they increase with the increase in the reference temperature value. The decrease in both of them is small because of the small changes in the reference temperature during the daytime on 21st of January 2016.

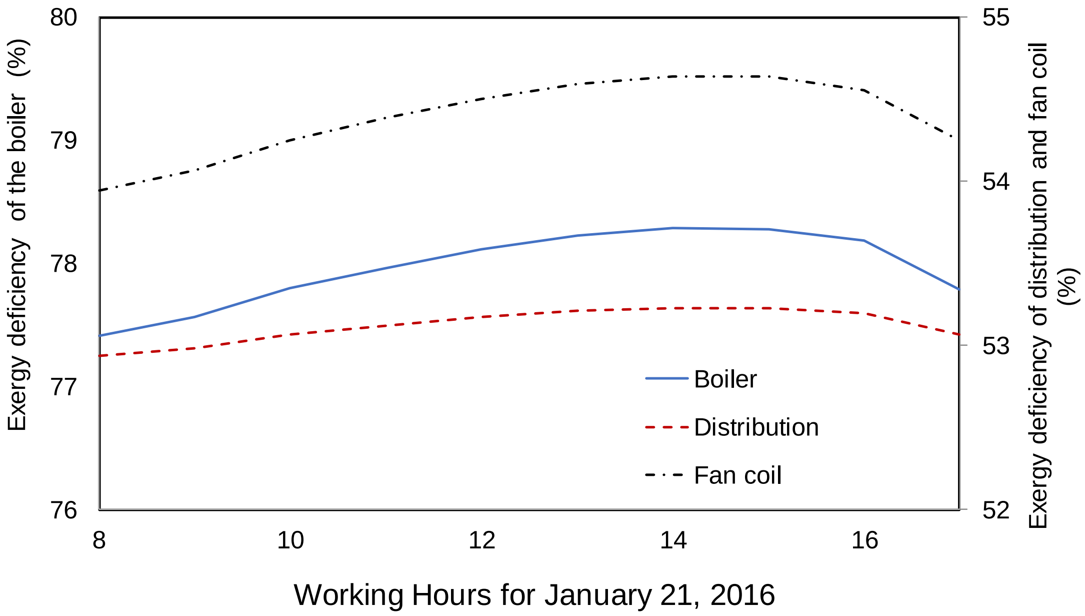


Figure 5. 8 The exergy deficiency vs. working hours of the SCOLA Building on January 21, 2016.

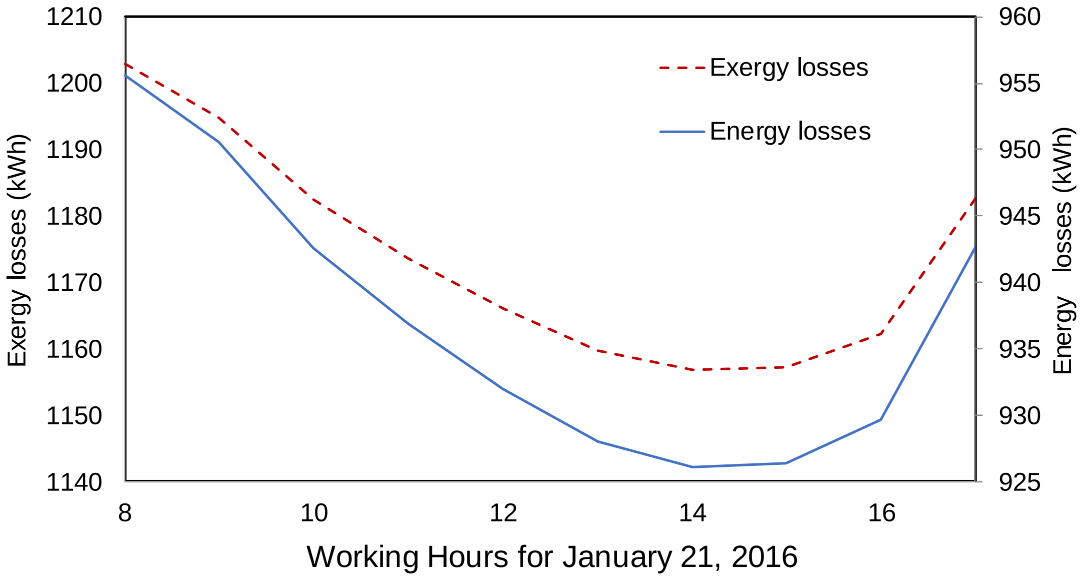


Figure 5. 9 The energy and exergy losses vs. working hours of the SCOLA Building on January 21, 2016.

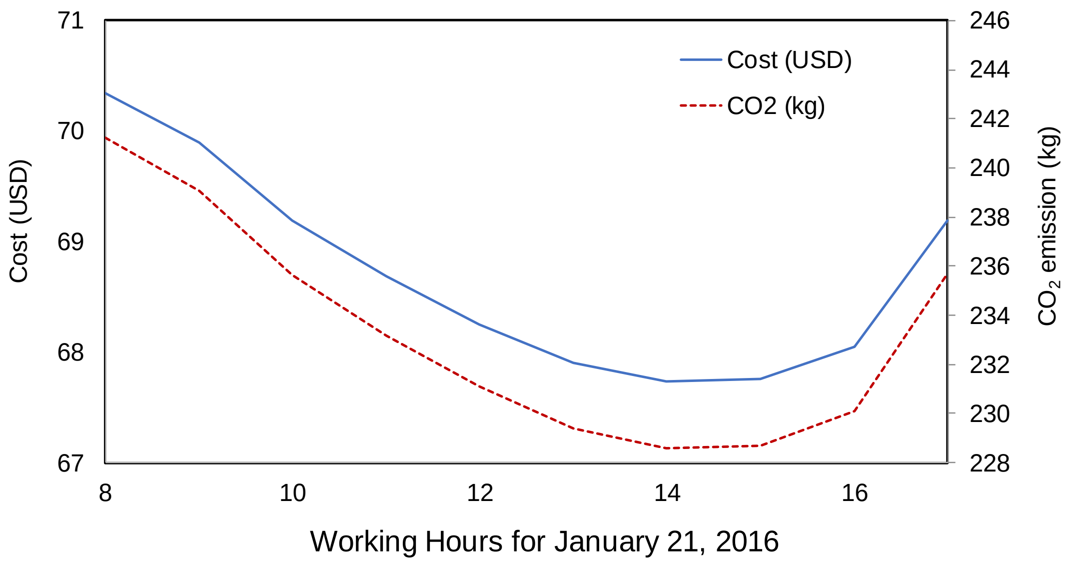


Figure 5. 10 The demand energy cost and produced CO_2 emissions changes throughout the working hours of the SCOLA Building on January 21, 2016.

In addition to the energy and exergy analyses, the exergoeconomic analysis was carried out in dynamical fashion to achieve accurate cost predictions. Figure 5.11 shows the exergetic cost coefficients results for the analysis of working hours of the 21st of January 2016. The analysis is given for the heating system components, including boiler, distribution pipes, and fan coil. The coefficients fluctuate during the day because their values are proportional to ambient temperature change. The rise in ambient temperature causes an increase in the components deficiencies and leads to increasing the values of coefficients. However, the total cost does not increase in the warmer months like April or October because the reduction in energy demand is greater than the rise in the component's deficiencies, as it was mentioned previously.

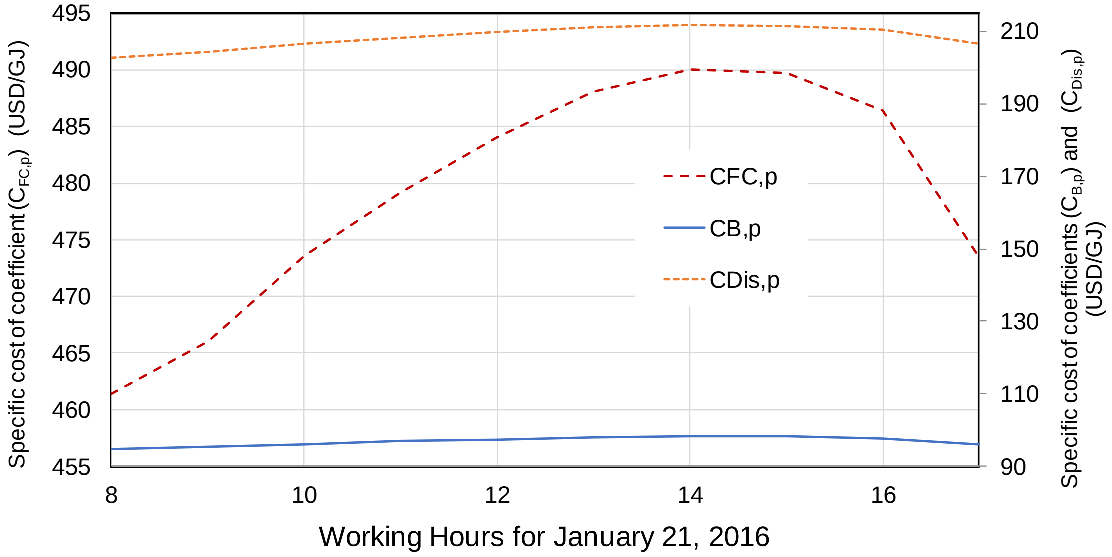


Figure 5. 11 The exergetic cost coefficients vs. working hours of the SCOLA Building on January 21, 2016.

The monthly variation of energy and exergy demands are shown in Figure 5.12. The largest energy consumption occurred in December 1,372 GJ, whereas the exergy demand is equal to 1,326 GJ. The least consumption occurred in September because of the higher ambient temperature; for September, the energy and exergy demands were 231 GJ and 150 GJ, respectively. Energy consumption in February was lower because of fewer days.

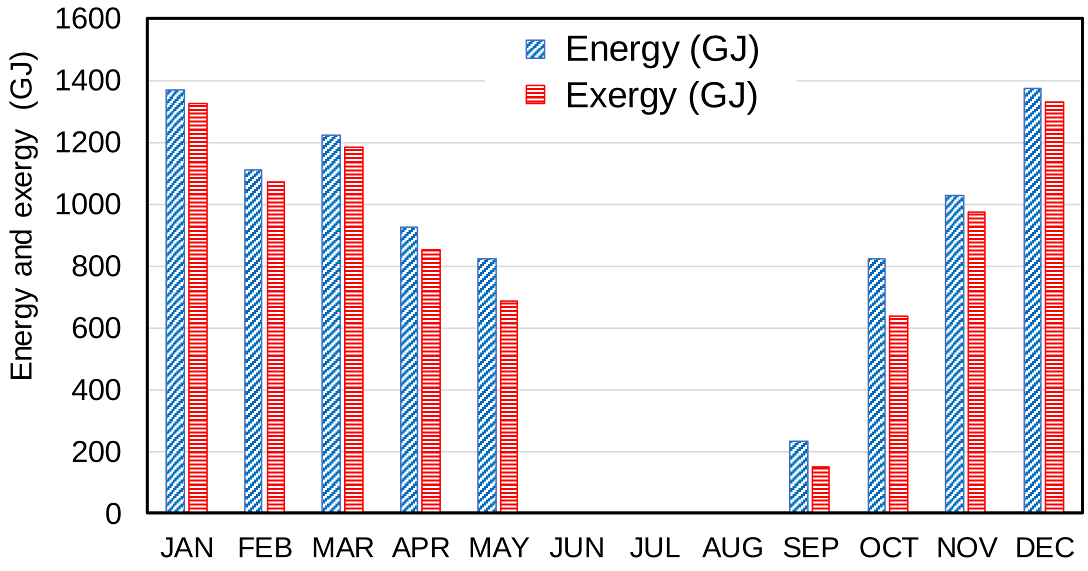


Figure 5. 12 Monthly energy and exergy demand for 2016.

The cost and CO_2 emission of energy are directly connected to the energy consumption as shown in Figure 5.13. The highest cost occured in December and January, which is worth close to 21,000 USD (based on natural gas, electricity, and CO_2 emission prices equal to 13 USD/GJ (Bagdanavicius et al., 2012), 0.072 (USD/kWh) (Turkish Statistical Institute, 2017), and 0.028 USD/kg-CO_2 (Kossoy & Peszkom 2015), respectively. The cost decreases in other months occurred because of the increase in the ambient temperature. Similar to the energy and exergy demands, the month of September has the least compared to other months.

The comparisons given in Figure 5.13 are important, as they provide a guidance to designers and investors about the cost of energy and CO_2 emissions for taking precautions during the design phase. We note that the CO_2 emission amount does not differ from the energy cost because it relates directly to the energy consumption. Its value is calculated by applying the environmental analysis that is based on the energy consumption amount for estimating the amount of CO_2 emission produced. The specific amount of CO_2 produced from electricity and natural gas are taken to be 0.38 kg/kWh (Whyte et al., 2012), and 53 kg/GJ (Website-Electricity CO_2 emission), respectively. The monthly changes for the CO_2 emission are quantified and depicted in the same figure.

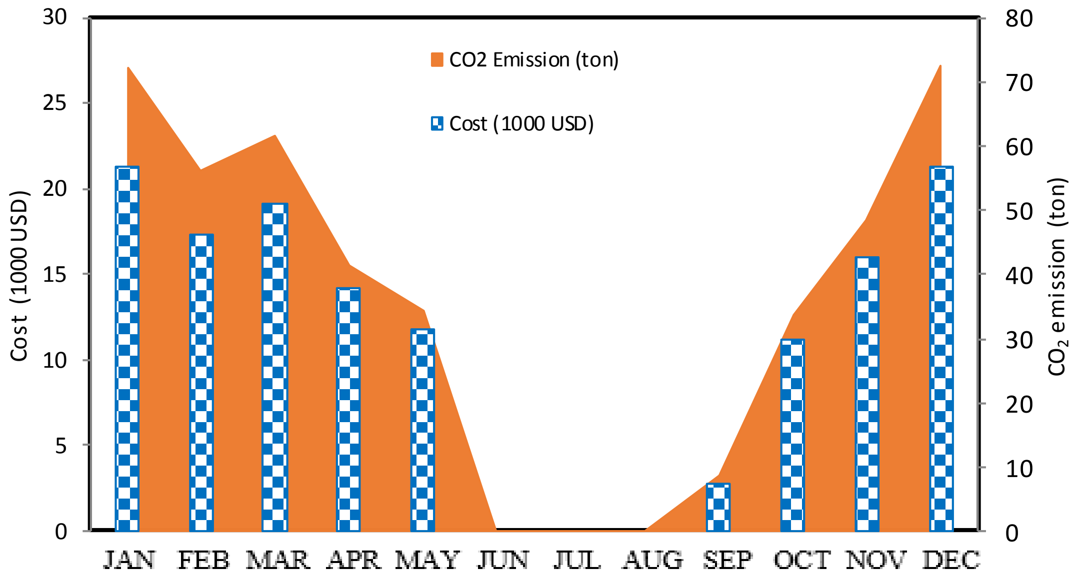


Figure 5. 13 Monthly cost (left axis) and CO_2 emission (right axis) of energy demand.

Based on the hourly calculated load, the annual energy demand of the building is equivalent to the total of hourly loads, which is estimated to be 1,772 GJ; the exergy demand is determined to be 77 GJ as shown in Figure 5.14. The annual contributions of all components of the building are quantified as well. The annual contribution of ventilation losses is 802 GJ while its exergy contribution is 35 GJ. Similarly, the costs of the rest of the component's losses can be estimated based on their annual exergy losses.

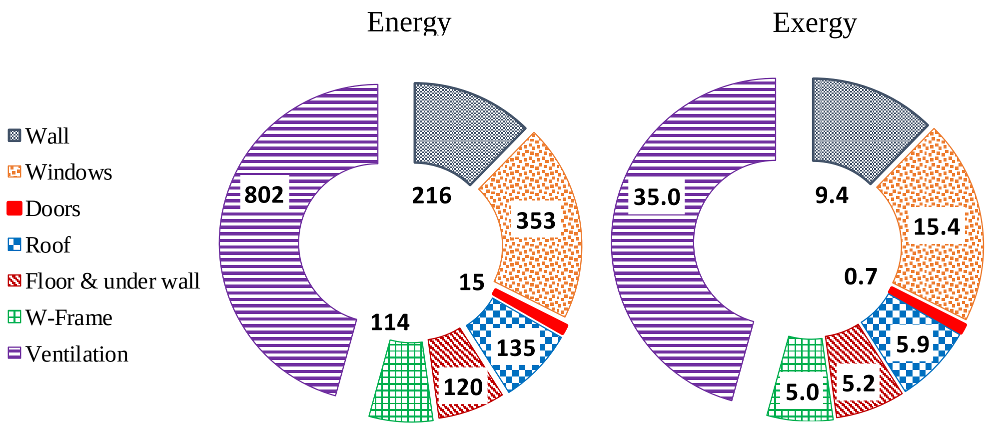


Figure 5. 14 Annular energy and exergy (GJ) contributions of the building components.

The annual energy and exergy flow through the system components were estimated in a dynamic analysis by accumulating the hourly values, as shown in Figure 5.15. The annual heating load was calculated to be 1,755 GJ, and its exergy value was 77 GJ. Furthermore, the total energy and exergy demands were 8,909 and 8,215 GJ, respectively. The energy efficiencies of boiler, distribution, and fan coils based on this analysis were 39%, 73%, and 95%, respectively, while their exergy efficiencies were 17%, 46%, and 44%, respectively. The annual energy losses of the boiler, distribution, and fan coil were 3,997 GJ, 657 GJ, and 76 GJ, respectively. The exergy losses of the same components were 4,712 GJ, 532 GJ, and 257 GJ, respectively.

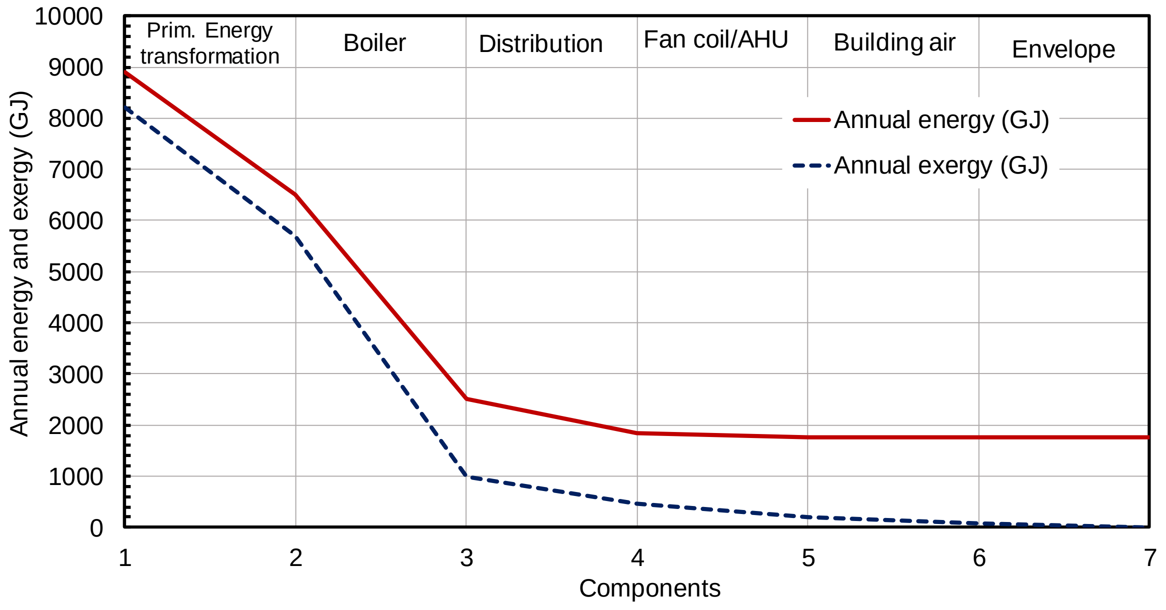


Figure 5. 15 Annular energy and exergy (GJ) flows through the system components.

Daily comparisons between static and dynamic analyses results are shown in Figure 5.16. The energy demand and the cost are for the day of the 21st of January, which were calculated for different values of reference temperatures. A change in reference temperature can reduce the divergence to be less than 1%, whereas a wrong temperature used in static analysis can increase this divergence. The monthly deviation between static and dynamic analyses results can be seen in Figure 5.17. There was a particular temperature for each month that minimizes the divergence between the monthly results of the two analyses. This divergence was proportional with the period that need to be analyzed. For instance, the deviation of the monthly results of the static analysis was larger than the deviation of the one-day results of the same analysis relative to the same intervals results of the dynamic analysis, as shown in Figures 5.16 and 5.17. On the other hand, Figure 5.18 explains the annual divergence for a specific temperature considered as the reference temperature in the static analysis. The average temperature value that caused the largest difference between the two analyses (static and dynamic) was estimated to be 14^{o} C.

We can question whether there is an optimum average temperature yielding the best match between the static and dynamic analyses. Figure 5.19 shows that the static analysis results may diverge relative to dynamic analysis results as a function of the average temperature value used. If the average temperatures were 7, 12, 10, 15, 18, 18, 13, and 7° C was for January, February, March, April, May, October, November, and December, respectively, the results of the static analysis results would be closer to dynamic results. Using these average temperatures, the differences between the two analyses for energy demand, the exergy demand, the cost, and the CO_2 emission were equal to 1%, 3%, 2.5% and 1%, respectively. Determining the temperatures that lead to optimum matching between the static and dynamic analysis does not eliminate the necessity for dynamic analysis since these optimums can be determined only if a dynamic analysis is performed. In addition, the dynamic analysis always reveals the time of maximum demand that cannot be estimated by static analysis.

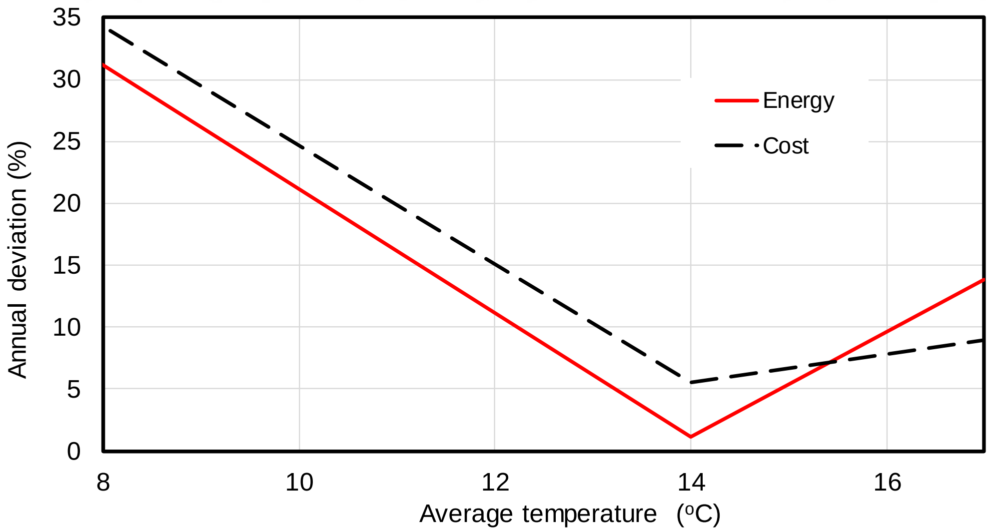


Figure 5. 16 The daily difference between static and dynamic results for different values of reference temperature.

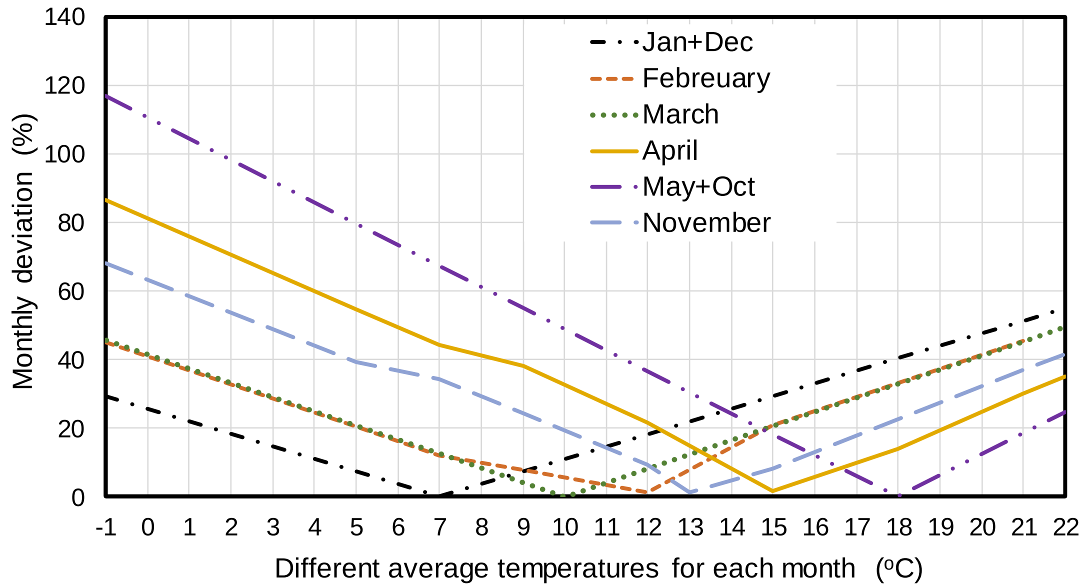


Figure 5. 17 The monthly difference between static and dynamic results for different values of reference temperature.

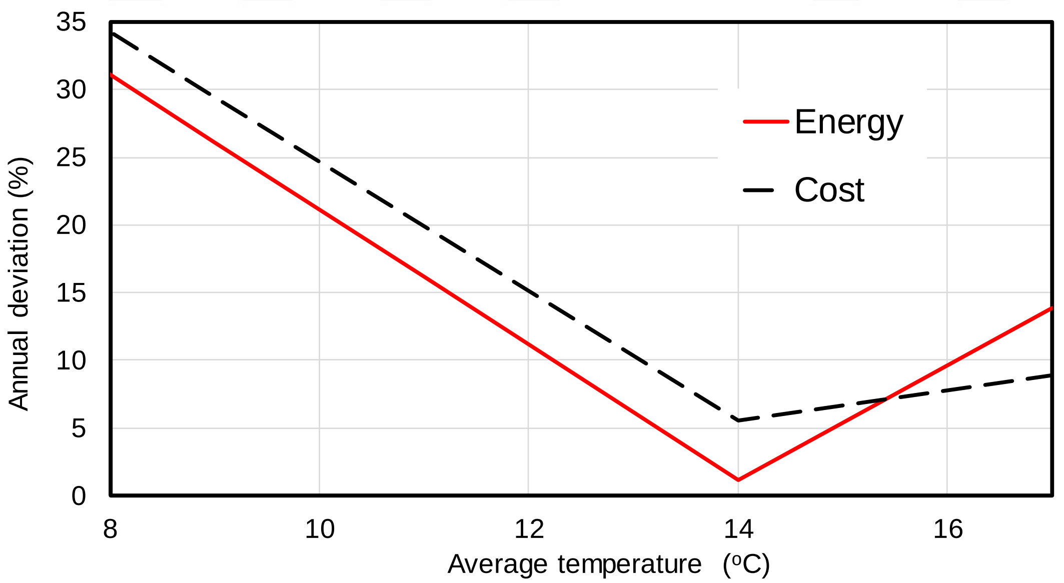
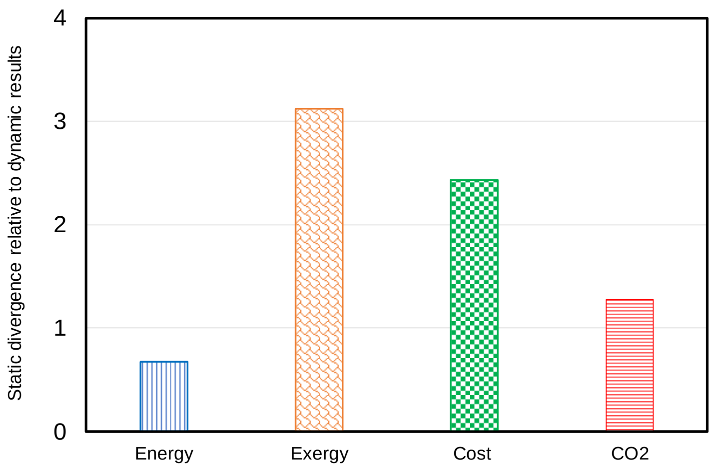


Figure 5. 18 The annual difference between static and dynamic results for different values of reference temperature.



Month	Average temp (ºC)
Jan	7
Feb	12
Mar	10
Apr	15
May	18
Sep	Ignored
Oct	18
Nov	13
Dec	7

Figure 5. 19 The difference between the static and dynamic results for the entire heating season if a specific reference temperature is considered for each month.

5.2 *The Improving Processes*

A pre-design tool, ECBCS Annex 49 (Schmidt, 2009), was used to estimate the energy and exergy demand of the SCOLA Building. Annex 49 is a task-shared international research project within the framework of the International Energy Agency (IEA) program on energy Conservation in building and community Systems. Its aims are the development of assessment and analysis methodologies that lead to a reduction of the exergy demand in building, and, consequently, CO_2 emissions. Moreover, it focuses on the development of exergy distribution, generation and storage system concepts (Schmidt & Ala-Juusela, 2004; Schmidt ,2009l Torio & Schmidt, 2011).

The energy and exergy efficiencies of the heating system were calculated dynamically based on energy and exergy balances of each component for five cases. The measured and design data of the system that was provided by Ozyegin University Energy Distribution Center was used for this purpose. The economic aspect was considered by applying exergoeconomic analysis dynamically. In addition, the enviro economic impact was considered in determining the cost of generated emissions due to energy consumption. Lastly, a detailed comparison between these five cases was performed.

Figure 20 shows the annual energy flow through the building and its heating system for all cases. It can be observed that the highest energy demand is for the first case, which depends only on the architectural design feature and the first installed heating system. The importance of reducing the heating load of the building and the effect of this reduction on the total energy demand can be seen in Case 2 which explains the effect of the ground air heat exchanger (GAHX). Using the heat exchanger can reduce energy demand around 4% relative to the first case. Better reduction in energy demand can be seen in the third case has an 8% reduction (improvements in the thermal insulation of walls, roofs, and windows by 50%, 25%, and 23%, respectively). Using a PV panel (Case 4) can cause more reduction (10%) whereas applying the tri-generation system (Case 5) leads to a 29 % reduction in the energy demand. Integrating all of the improving processes simultaneously (Case 6) decreases the energy demand by 41%. This improvement in building performance has the potential to lead to significant reduction in energy demand all over the world.

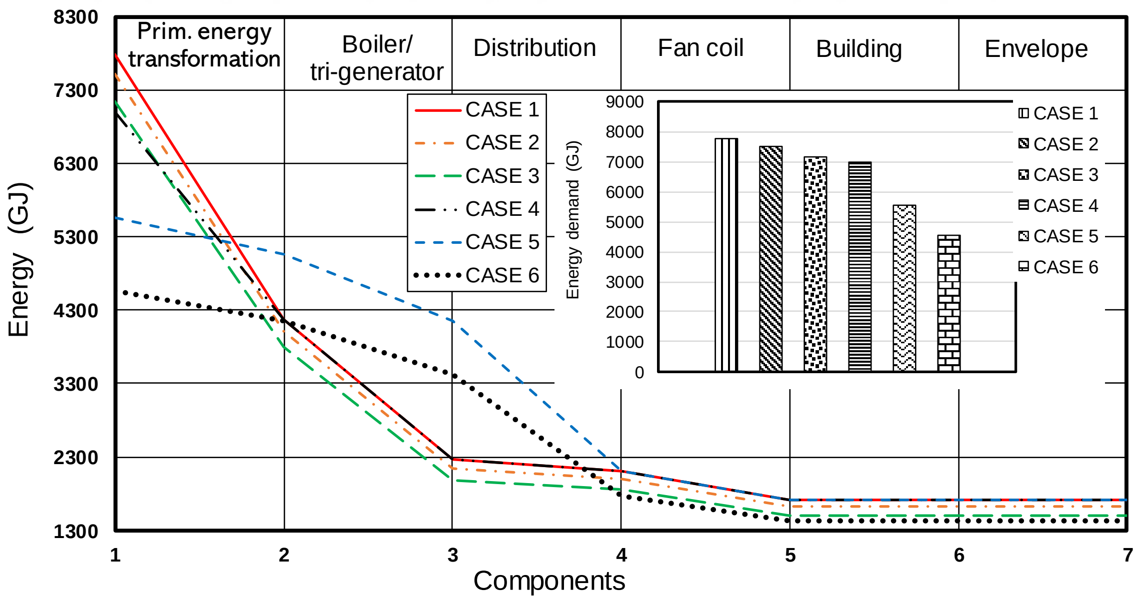


Figure 5.20 The annual energy flow from the source to the building envelope.

In addition to energy flow, annual exergy flows were also dynamically estimated in Figure 5.21 for all cases of the building and its heating system at each stage. The exergy demand reductions in the second and third cases relative to the first case were 5% and 8%, respectively. It can be inferred from the exergy reduction (18%) that the PV panels can contribute significantly to the enhanced performance of a building. In contrast, the fourth case exergy demand reduce around 36% relative to the first case whereas, the fifth case was found to provide the maximum reduction in exergy consumption, which was 48%. The figure 21 justifies the use of a tri-generator to reduce energy demands and consequently the CO_2 emission.

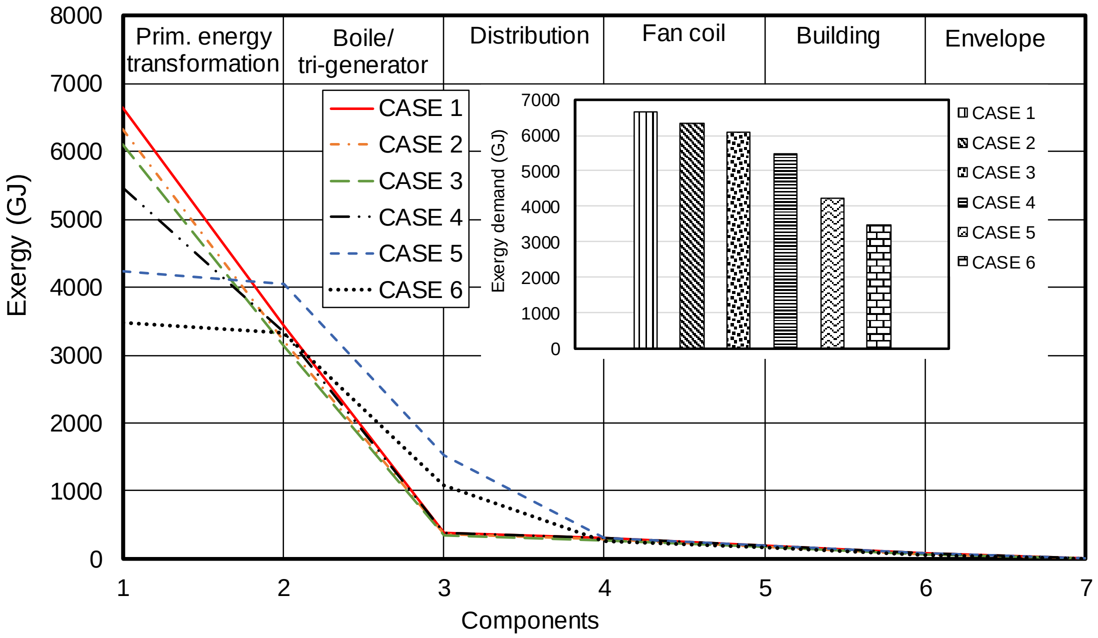


Figure 5. 21 The annual exergy flow from the source to the building envelope.

The energy before and after each component, for all cases, are presented in Figure 5.22 which, in other words, represents the losses in each component (Schmidt, 2004a, 2009). It can clearly be stated that all of the improving processes improved the building's performance, but the smallest number of losses occurred in the sixth case for both components: the primary energy transformation and the boiler/tri-generator stages. In the fifth and sixth cases, the distribution had the largest loss of all the other cases because the tri-generator produces all consumed powers, whereas, in the first four cases after distribution stage, there is only the energy for heating. This difference leads to this large loss of distribution in these two cases. In the fan coil/AHU component, the losses in the second case are less than its value in the fifth case because the heating load, in this case, smaller than all the others.

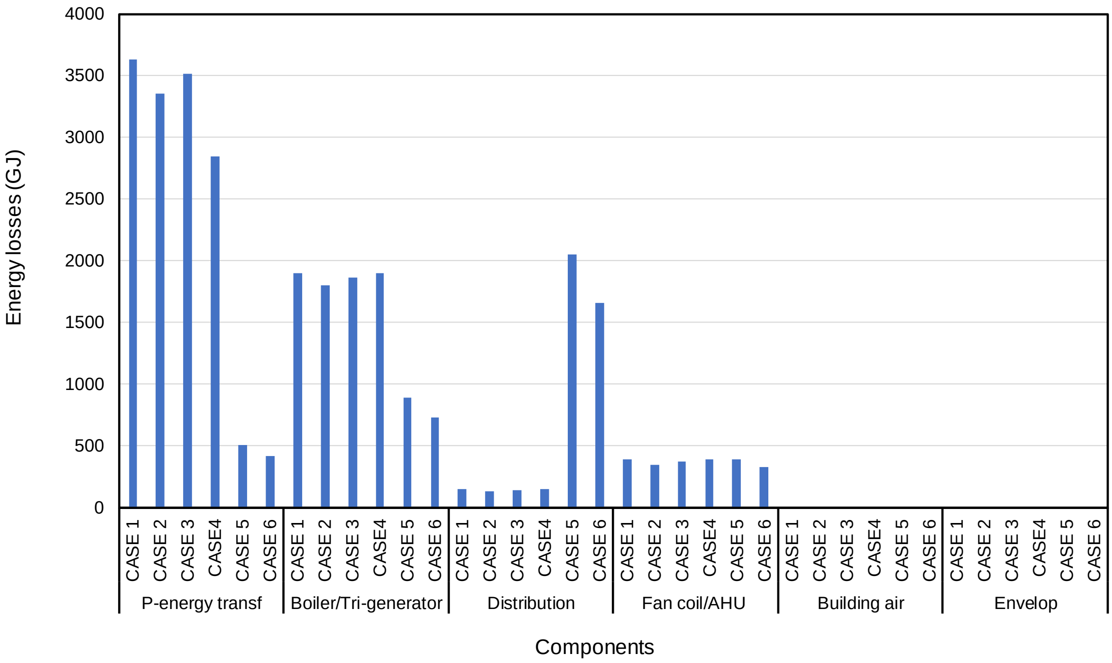


Figure 5. 22 The annual energy loss for components for all cases.

Exergy losses (or destructions) do not differ from the energy losses as seen in Figure 5.23. Case 1 has the maximum losses, then case 2, case 3, case 4, and case 5; and the smallest losses were in Case 6. The highest losses of all cases occurred in the generation stage (boiler or tri-generator) stage whereas the second largest losses in these cases occur in the primary energy transformation stage even though the losses of the first four cases is higher than the losses of the last two cases. Similar to the energy losses in Figure 5.22, the distribution stage had the highest exergy losses for the same reason. The exergy losses through the rest of the components are similar to the energy losses through them.

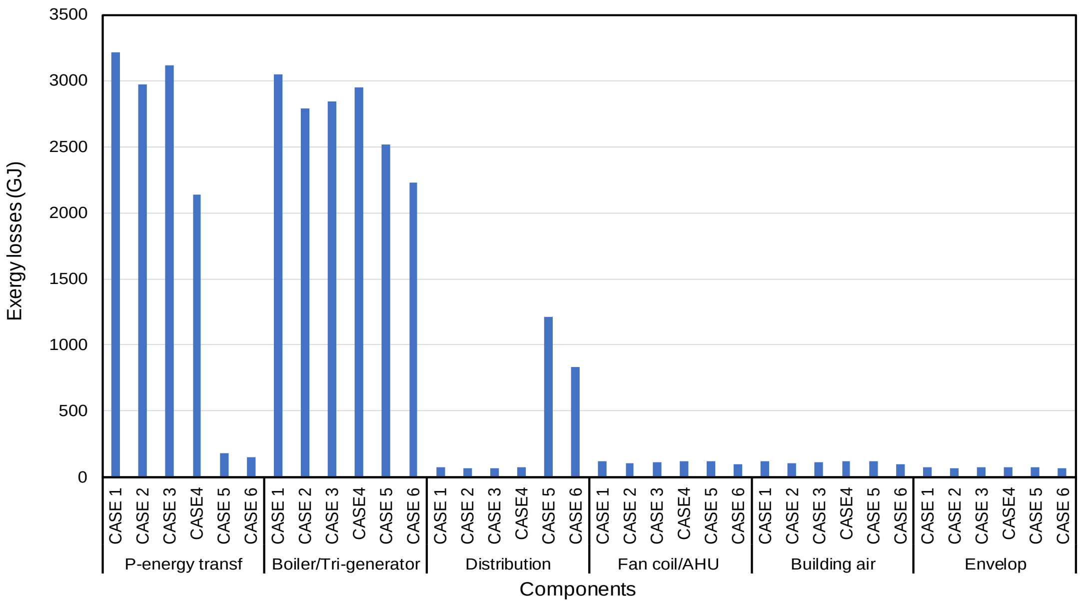


Figure 5. 23. The annual exergy losses of components for all cases.

In addition to the energy and exergy flows and losses, the energy consumption cost is quantified for all cases based on a dynamic exergoeconomic analysis. The costs of energy consumption of all cases are presented in Figure 5.24. The figure gives an overview of the importance of alternative sources of energy. In Case 2, a 4% reduction in annual energy demand was achieved using the ground air heat exchanger (GAHX) which corresponds to a savings of 5,000 USD annually. This reduction was larger in Case 3 where the thermal insulation of walls, roofs, and windows was increased. It can be seen this reduction was around 8 % with a savings of 8,000 USD annually. Case 4 provides a reduction of 10% with a savings of 14,000 USD annually, by using PV panels to provide electricity from solar energy. Moreover, a 37% reduction in annual energy demand could be reached by utilizing a tri-generator to provide both electricity and hot water. When all improving processes are integrated with Case 1 to form the sixth case, a 41% reduction in energy demands with 48,000 USD could be achieved. These values provide a real vision for the future of green buildings.

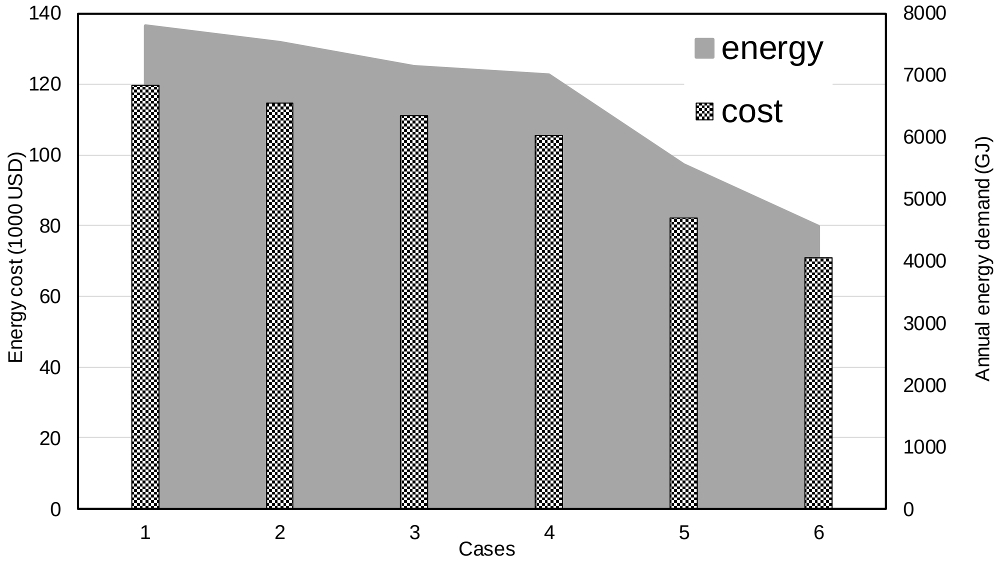


Figure 5. 24. The annual energy demands and their costs for all cases.

The environmental considerations of the system are in Figure 5.25. The second, third, and fourth cases reduced CO_2 emission 4%, 8%, and 15%, respectively. A 51% reduction can be achieved by implementing a tri-generation system in the fifth case. The overall system improvements corresponding to the sixth case resulted in a 60% reduction in CO_2. This value of reduction is very significant and deserves financial investment. This significant reduction in CO_2 emission from buildings should lead the way to better design for energy production modalities for buildings and should reduce their negative impact on climate change.

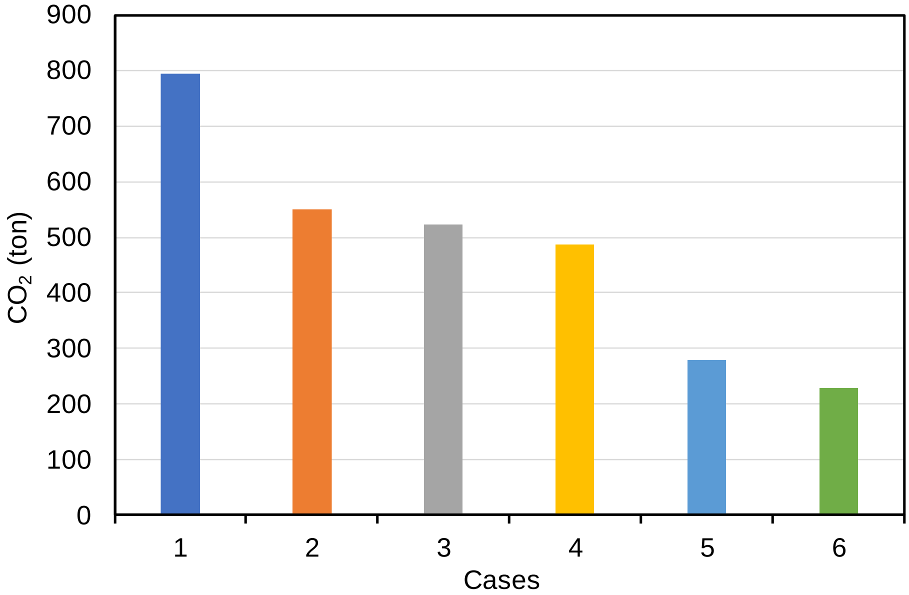


Figure 5. 25 The annual CO_2 emission (ton/yr.) for all cases.

Figure 5.26 reveals the exergy efficiency and sustainability index of the building for each case. These two values indicate how efficient the energy demand is that is used by the building and its heating system. For the first (original) case, the exergy efficiency and sustainability index are 3% and 1.03 %, respectively. The values of the variables of the second are identical to their values in the first case. The total exergy demand and the exergy load of the building were reduced, but even the exergy efficiency and sustainability index of this case were still identical with those for the baseline case. The sustainability indexes of the third, fourth, fifth, and sixth cases are 1.031, 1.036, 1.048, and 1.05, respectively. These values provide the clear concept that more steps should be taken to improve the exergy efficiency and sustainability index of the building.

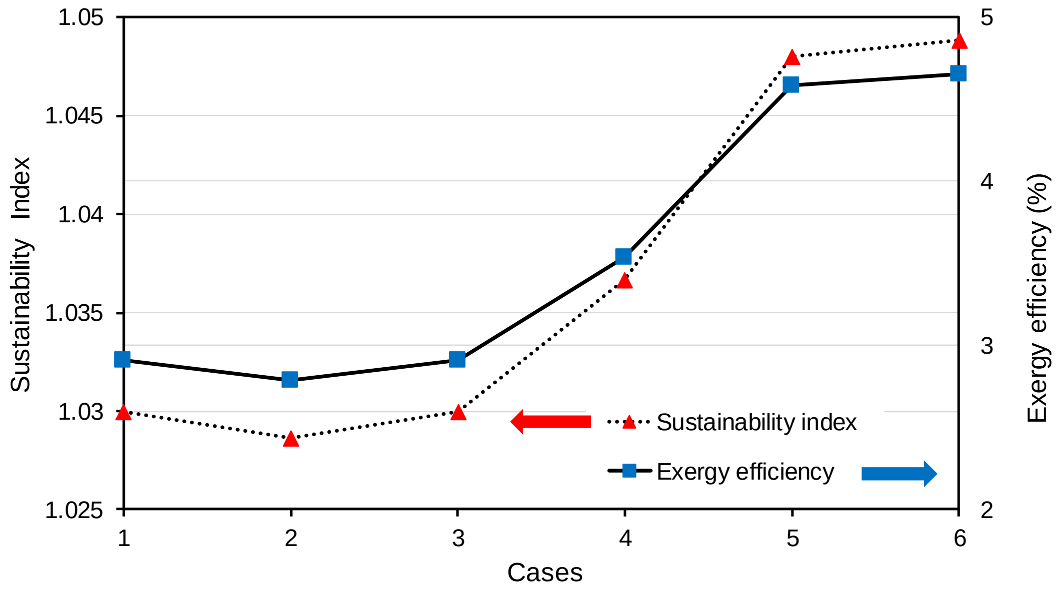


Figure 5. 26 The exergy efficiency and sustainability index of each case.

After discussing the energy reduction that can be achieved by applying all these cases, the economic and CO_2 reduction benefits are illustrated in Figure 5.27 to highlight the exclusive details of these improvements. A developed Marginal Abetment Cost Curve (MACC) is presented in this section. The Y-axis represents the cost saving of all improving processes relative to the original case, whereas the X-axis is the CO_2 emission reduction relative to the base scenario. The designers or investors can make prediction between these cases, not only for the economic aspect but also for the environmental effect, simultaneously by using one curve. They can choose their priority based on both the economic and environmental results of the curve, and this is the usefulness of the curve. The importance of the architectural aspect for energy demand and, consequently, for a building's cost and carbon dioxide emission should be noted. 8,400 USD and 46 ton of CO_2 can be saved by improving the insulation of walls, roofs, and windows. Moreover, the PV panel had an influential effect that saved around 13,900 USD and 83 ton of CO_2 emission annually. The greatest saving of both energy and emission occurs by using a tri-generation system with savings of 37,240 USD and 290 ton of CO_2. This case illustrates the importance of applying such a system to buildings. Applying all cases simultaneously can also be seen in the same figure.

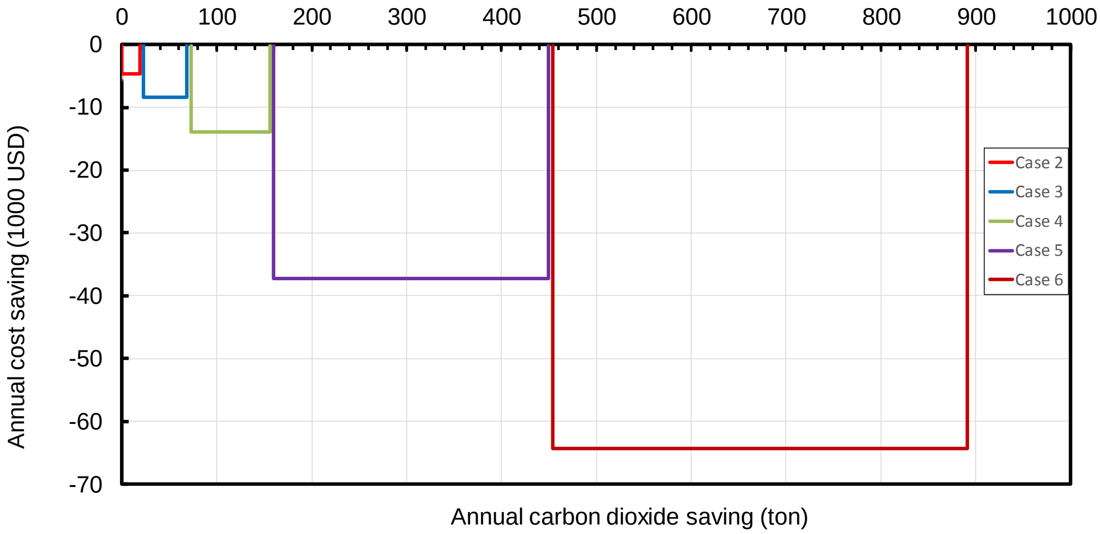


Figure 5. 27 The exergy efficiency and sustainability index of each case.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

In this study, we presented a comprehensive exergetic, exergoeconomic, and enviroeconomic analysis of an existing high-performance building. Both the static and dynamic analyses were applied to a university building at the campus of Ozyegin University in Istanbul. The pre-design tool in Annex 49 was used to utilize the analysis and EES software was employed for the calculations (the steps of EES can be seen in Appendix B). The energetic and exergetic efficiencies of all components of the heating system were calculated using the real-time measured data obtained from the building monitoring system. The heating load of the building and the contributions of the building components were estimated, and the energetic and exergetic losses through those components were determined. Furthermore, an exergoeconomic analysis was applied to the building to determine the cost of CO_2 emissions and the exergy cost coefficients.

In the first part of the study, the analysis was applied in an hourly fashion for the entire heating season, using the available hourly heating demand data. The summer months were not considered in the analysis. The effects of the reference temperature (ambient temperature) on the energy and exergy demands, the heating system components efficiencies and their losses, the cost, the CO_2 emissions, and the exergetic cost coefficients were determined. The monthly energy and exergy demand, the cost, and the CO_2 emission were estimated.

In this part, a detailed performance analysis of an existing high-performance building was carried out with six cases based on the architectural effect and different alternative energy sources. The first case represents the original design situation of the building and its heating system. The second case was based on the addition of a ground air heat exchanger that conditions one floor of the building. An architectural effect (reducing the U-overall of walls, roofs, and windows 50%, 25%, and 23%, respectively) is the third case. The fourth case corresponded to the use of PV panels covering the building roof. The fifth case utilized a tri-generator for providing heat, electricity, and hot water. The sixth case was a comprehensive scenario, which integrated all of the cases together. Exergetic, exergoeconomic, and enviro economic analyses of the building were dynamically performed. The energetic and exergetic efficiencies of all components of the heating system were determined, using real-time measured data obtained from the building monitoring system. The energy and exergy flows, the components losses, the energy costs, and the CO_2 emissions were calculated dynamically for the entire heating season. Furthermore, the exergy efficiency and sustainability index of the building for all cases were determined.

Based on these calculations, we can list the following major conclusions:

1- Implementation of the exergy analysis along with the energy analysis allowed us to have a comprehensive view of the energy and exergy flow through the components of a building, which helped to determine the cause of the largest losses.
2- Exergoeconomic analysis is essential in deciding which processes or components need to be modified for building operations.
3- Dynamic analysis yielded much more reliable results compared to static analysis since there are large deviations between them.
4- The deviation of the static results relative to the dynamic could be minimized by estimating a proper reference temperature, which needed to be done a priori for a given climatic zone with certain type of buildings.

5- The references temperatures that minimized the divergences between the static and dynamic analyses could be estimated daily, monthly, and annually. For the Istanbul climate, a reference temperature of 14° C was found to yield the optimum results by a static analysis of an academic building.

6- The dynamic analysis provided a clear picture of a building's performance and should be preferred over a simpler static analysis.

7- The second, third, fourth, and fifth cases allowed reductions of the total energy demand od around 3%, 10%, 29%, and 36%, respectively, relative to the original design. This means that the addition of the tri-generation system had the most dramatic impact on the building's performance.

8- The annual exergy demand could be reduced to 5%, 18%, 36%, and 43% by the new scenarios for the second, third, fourth, and fifth cases, respectively, showing the potential broader impact of each improvement. Again, the addition of the tri-generation system is the most important improvement followed by the addition of the solar PV system.

9- The results show that there are potential improvements in the area of architecture, even in such high-performance buildings.

10- Maximum enhancement in building performance can be achieved by using a tri-generation system instead of traditional systems.

11- The fifth case could achieve the best improvement in exergy efficiency (36%) after the six case which represents the accumulation of all of the improving process (48%). Also, the best improvement in sustainability was around 2% by applying the sixth case.

12- The exergy efficiency and sustainability indices of the tri-generator system for the fourth case are 36% and 1.56. They are 6% and 1.06 % for the sub-component of the boiler.

13- Based on MACC analyses, the best cost and CO_2 saving could be achieved by applying the fifth case.

14- Constructing the MACC based on exergy analysis could achieve accurate results because of the accuracy of exergy analysis, which had not been applied to such calculations before.

APPENDIX A

EXPERIMENTAL DATA RESOURCES

In this Appendix, the details of the raw data used for the SCOLA Building are provided.

A.1. PV-panels data

The energy production from the solar PV-panels can be found using the following link. However, a special permission must first be obtained from Ozyegin University to access the data. http://91.121.76.158:8080/Need4B/Login.action). All data are being recorded in 15 minutes intervals. The raw data is in an excel file that consists all data of 2016. Following table (Table A.1) shows an example of the data that involves the data of 21st of each month for two different times (morning at10:00 and evening at 15:00.

Table A. 1 Electrical energy produced by PV-panels of Scola (only for hours of 10:00 and 15:00).

Day-Month	Hours	PV production (kWh)
21-Jan	10:00	100
21-Jan	15:00	609
21-Feb	10:00	112
21-Feb	15:00	691
21-Mar	10:00	79
21-Mar	15:00	474
21-Apr	10:00	126
21-Apr	15:00	641
21-May	10:00	165
21-May	15:00	724
21-Jun	10:00	231
21-Jun	15:00	765
21-Jul	10:00	80
21-Jul	15:00	614
21-Aug	10:00	286
21-Aug	15:00	827
21-Sep	10:00	255
21-Sep	15:00	715
21-Oct	10:00	102
21-Oct	15:00	207
21-Nov	10:00	304
21-Nov	15:00	428
21-Dec	10:00	206
21-Dec	15:00	504

Fig. A.2.1. The schematic for the ground-based heat pump used at SCOLA.

Jan	94847
Feb	110371
Mar	95319
Apr	95790
May	82524
Jun	97341
Jul	100460
Aug	96035
Sep	112728
Oct	103001
Nov	98506
Dec	93788

A.2. Air Ground Heat Exchanger data

The following set of data are for ground-based heat pump for SCOLA. These data are taken from an electronic system at the Energy Distribution Center (EDS) of Ozyegin University Figure A.2.1. The photograph shows the places where the temperature data are collected.

All data of the Air Ground Heat Exchanger can be seen in the following link (http://oras2-PC/Total/controll/web/sites/ozu/105.aspx)

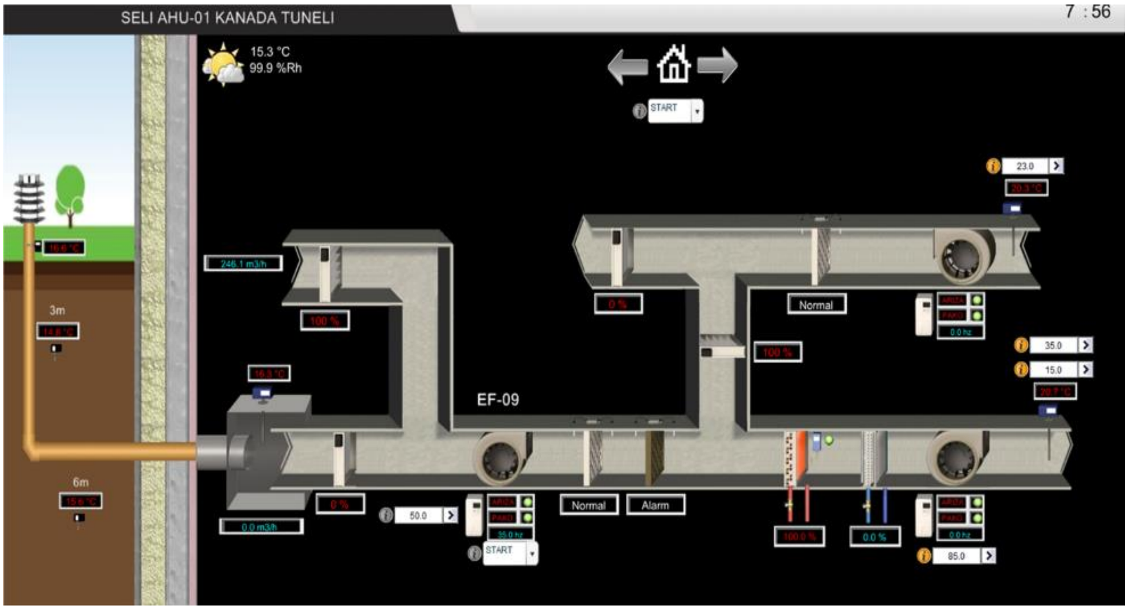


Figure A.2. 1 The schematic for the ground-based heat pump used at SCOLA.

A.3. Boiler data

The data for the boilers is also available from the system at EDS. The details are highlighted on the following Figure A.3.1.

All data of the boilers can be seen in the following link (http://oras2-PC/Total/controll/web/sites/ozu/409.aspx)

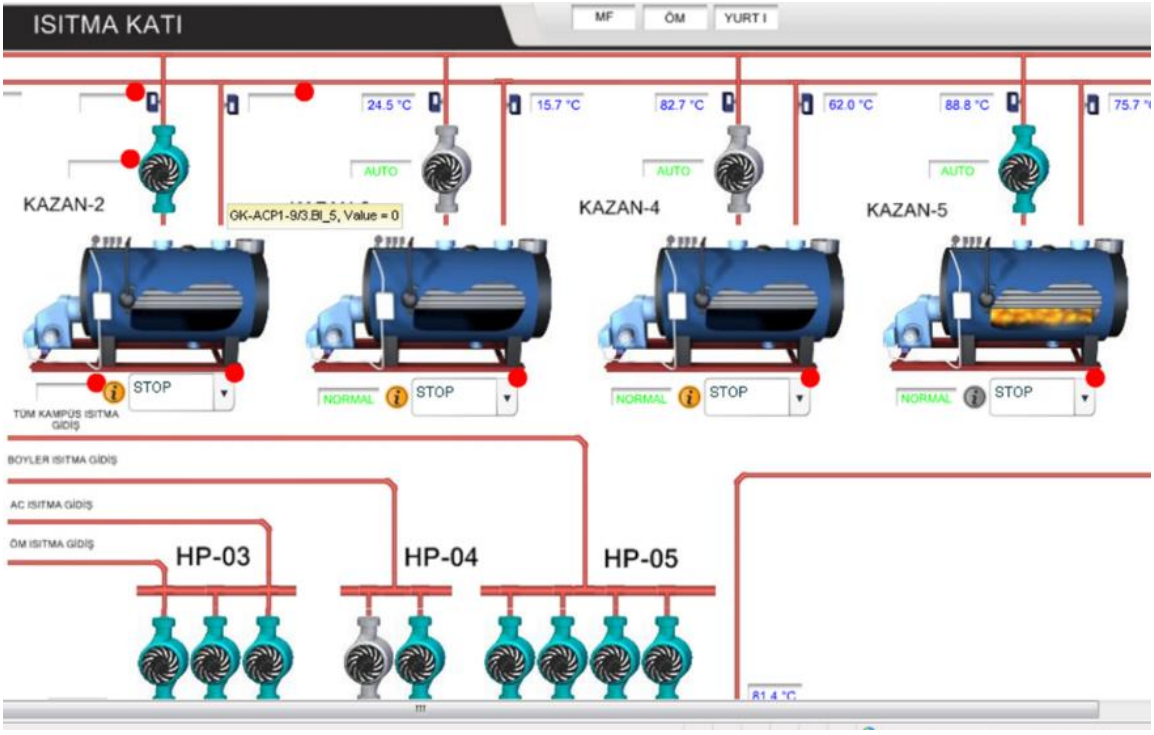


Figure A.3. 1 The schematic for the boiler system available at the Ozyegin University Energy Distribution Center (EDS).

A.4. Trigeneration system:

The operation data for the trigeneration system can be downloaded from a specific link for the tri-generation system at EDS (Figure A.4.1).The temperature of all tri-generation system components can be seen in this link. Again, special permission should be given by the University to open this link (http://10.100.79.194:5800). Figure A.4.2 shows the mechanical and electrical experimental data. Mechanical data involves the temperatures of input and output hot water that we used in this study. Electricity energy also can be seen in the same figure.

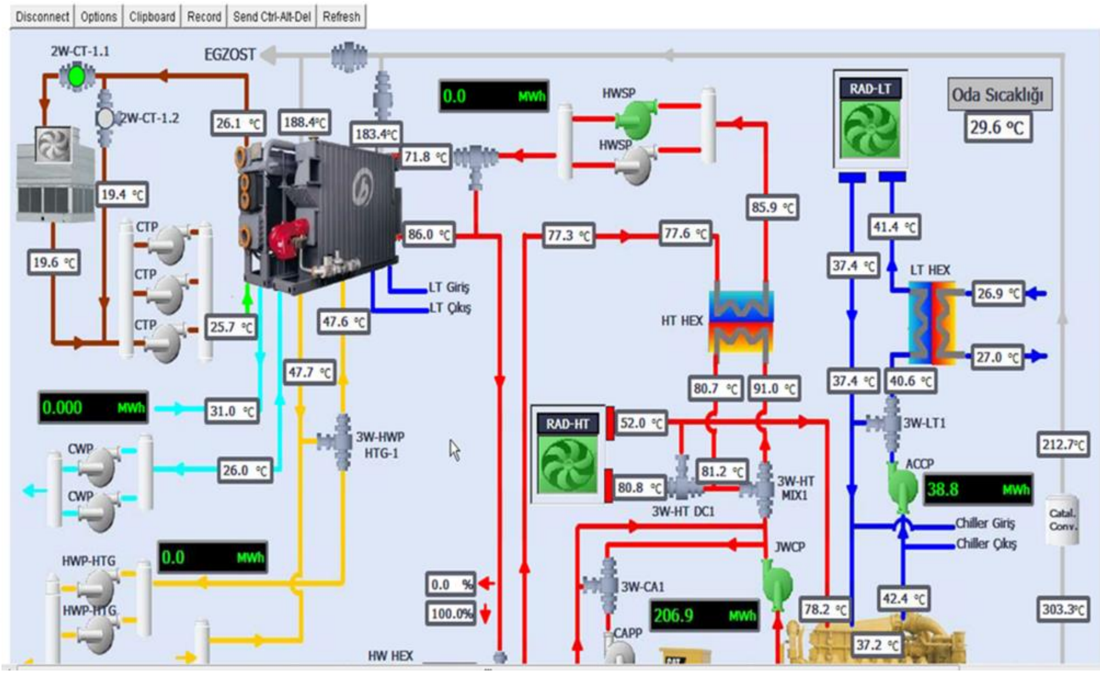


Figure A.4.1 The schematic for the trigeneration system available at the Ozyegin University Energy Distribution Center (EDS). The data are available at the specified nodes shown.

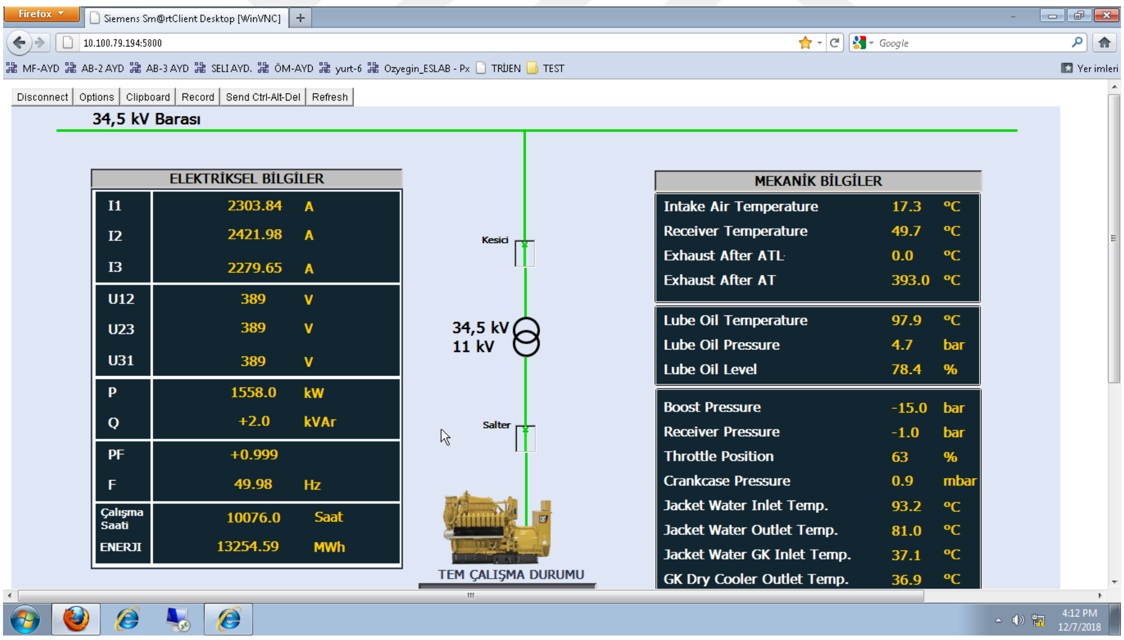


Figure A.4.2 The capture of the trigeneration system data. Mechanical and electrical data.

A.5 Architectural information

All architectural details of the SCOLA Building, with the specific thermophysical properties for walls, roofs, windows, doors, floors, shades, and other features can be found of the website of the CEEE Project New Energy Efficient Demonstration for Buildings (NEED4B) (http://need4b.eu/?page_id=11708&lang=en). This link provides many details of all buildings in different locations around Europe related to this project. Figure A.5.1 shows the website that involve the information of all projects.

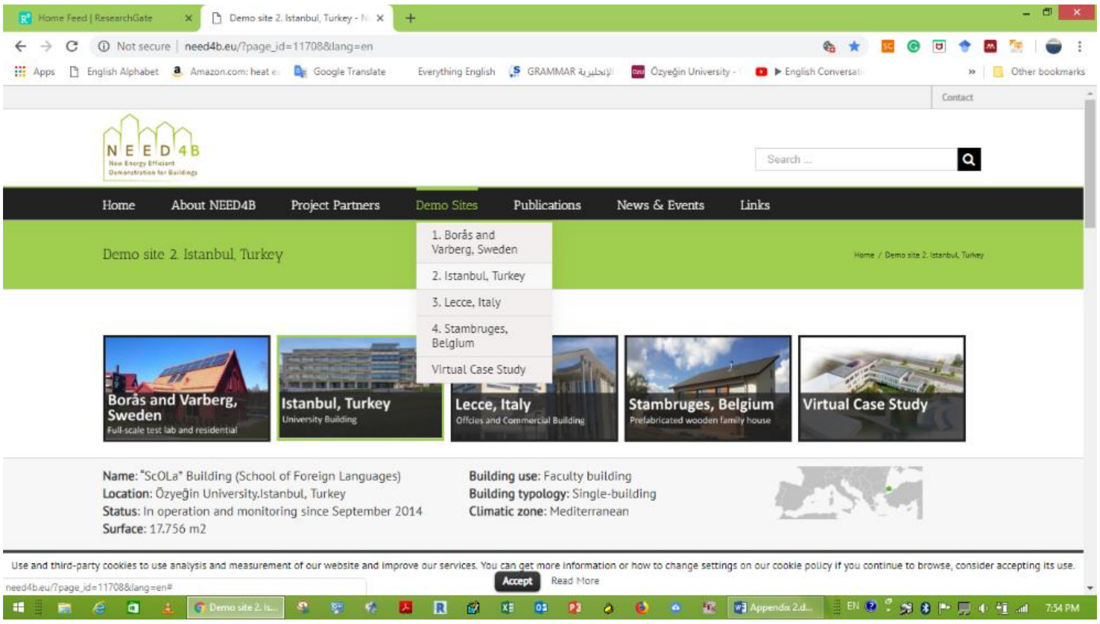


Figure A.5.1 The website for the CEEE Project New Energy Efficient Demonstration for Buildings (NEED4B) can be used to obtain all the architectural and mechanical details of the related buildings.

APPENDIX B

THE STEPS OF THE CALCULATIONS

This Appendix outlines all the steps taken for the calculations.

INPUT REQUIRED DATA

Room temperature (T_R)=23 ^oC
Cross area of the building= 17,756 [m^2]
Net area= 15,093 [m^2]
Building volume= 42,000 [m^3]
Total walls area= 3,788
Average wall overall heat transfer coefficient (U_W)=0.6 [W/m^2 K]
Total windows area=
Average windows overall heat transfer coefficient (U_g)=0.6 [W/m^2 K]
Total roofs area=
Average roofs overall heat transfer coefficient (U_R)=0.6 [W/m^2 K]
Number of occupancies = 1585
Specific occupancy load= 80 [W/m^2]
Specific appliances load= 4 [W/m^2]
Specific lighting load= 6 [W/m^2]
Ventilation change rate (n_v)= 0.45
Infiltration rate (n_{Inf})=0.16

↓

For i =1 to NHY (number of working hours/year)

↓

Description	Formulae
Heat transmission losses	$\dot{Q}_{trans} = \sum(U_k.A_k.).(T_R - T_o)$ (k-components (walls, roof, windows, doors))
Ventilation losses	$\dot{Q}_v = \rho_{Air}.V_{buil.}.n_v.(1 - \eta_{Hrecov})(h_R - h_o)$
Infiltration losses	$\dot{Q}_{inf} = \rho_{Air}.V_{buil.}.n_{inf}.(h_R - h_o)$
Heating demand of building (ϕ_h)	$\phi_h = (\dot{Q}_{trans} + \dot{Q}_v + \dot{Q}_{inf}) - (\dot{Q}_l + \dot{Q}_s + \dot{Q}_{occ} + \dot{Q}_{app})$
Exergy demand of building (ϕ_{EX})	$\psi_D = \phi_h.\left(1 - \frac{T_0}{T_R}\right)$

↓

From Energy an exergy balances of a Fan coil the energy and exergy efficiencies can be estimated for all values of weather temperatures. $(\eta_{e,FC})$ and $(\eta_{x,FC})$

↓

A

A

From Energy an exergy balances of the distribution network the energy and exergy efficiencies can be estimated for all values of weather temperatures. $(\eta_{e,Dis})$ and $(\eta_{x,Dis})$

From Energy an exergy balances of the boiler the energy and exergy efficiencies can be estimated for all values of weather temperatures. $(\eta_{e,B})$ and $(\eta_{x,B})$

Estimating the input energy and exergy for each component based on their energy and exergy efficiencies.

$$\dot{\phi}_{FC,in} = \frac{\dot{\phi}_h}{\eta_{e,FC}} \quad (36)$$

$$\dot{\psi}_{FC,in} = \frac{\dot{\psi}_D}{\eta_{x,FC}} \quad (38)$$

$$\dot{\phi}_{Dis,in} = \frac{\dot{\phi}_h}{\eta_{e,Dis} \cdot \eta_{e,FC}} = \frac{\dot{\phi}_h}{\eta_{e,Dis} \cdot \eta_{e,FC}} \quad (39)$$

$$\dot{\psi}_{Dis,in} = \frac{\dot{\psi}_{FC,in}}{\eta_{x,Dis}} = \frac{\dot{\psi}_D}{\eta_{x,Dis} \cdot \eta_{x,Fc}} \quad (40)$$

$$\dot{\phi}_{B,in} = \frac{\dot{\phi}_{Dis,in}}{\eta_{e,B}} = \frac{\dot{\phi}_h}{\eta_{e,FC} \cdot \eta_{e,Dis} \cdot \eta_{e,B}} \quad (76)$$

$$\dot{\psi}_{B,in} = \frac{\dot{\psi}_{Dis,in}}{\eta_{x,B}} = \frac{\dot{\psi}_D}{\eta_{x,Fc} \cdot \eta_{x,Dis} \cdot \eta_{x,B}} \quad (77)$$

After Determining the input energy and exergy the input energy and exergy to the energy primary transformation can be estimated based on these two equations.

$$ED = \phi_{B,in} . F_P + (P_l + P_{ve} + P_{aux,B} + P_{aux,Dis} + P_{aux,FC}) . F_{P,elec.} + \phi_{DHW} . F_{P,DHW}$$

$$XD = \phi_{B,in} . F_P . F_q + (P_l + P_{ve} + P_{aux,B} + P_{aux,Dis} + P_{aux,FC}) . F_{P,elec.} . F_{q,elec.} + \phi_{DHW} . F_{P,DHW} . F_{q,DHW}$$

B

B

After determining the input and output exergy values of all component it is time of exergoeconomic apply. First step is estimating the investment cost by kWh or GJ.

$$\dot{Z}_j = \frac{Cost_{inv}.CRF.\lambda}{NH.3600} \quad (89)$$

Then following equation can be applied to get the cost of product exergy

$$\dot{cost}_{in} + \dot{Z}_j = \dot{cost}_{out} \quad (88)$$

Repeat these steps for all hourly values of weather temperature for entire heating season.

IF i<NHY Repeat, IF i=NHY End

LIST OF REFERENCES

Açikkalp E, Aras H and Hepbasli A 2014 Advanced exergoenvironmental assessment of a natural gas-fired electricity generating facility *Energy Convers. Manag.* **81** 112–9

Açikkalp E, Hepbasli A, Yucer C T and Karakoc T H 2015 “Advanced exergoenvironmental assessment of a building from the primary energy transformation to the environment” *Energy Build.* **89** 1–8

Ahmadi P, Rosen M A and Dincer I 2011 “Greenhouse gas emission and exergo-environmental analyses of a trigeneration energy system” *Int. J. Greenh. Gas Control* **5** 1540–9

Akdemir M 2013 *Dynamic Energy and Exergy Analysis of An Existing Building in Iztech* (Izmir Institute of Technology. Izmir)

Akshey B, Swati B and Disha B 2018 “Green Buildings - A Step Towards Environmental Protection” *J. Waste Recycl.* **3** 1–4

Al-Alfi W 2018 “NG prices in Asian selling markets (Economy News)” *Thomson Reuters* Online: https://ara.reuters.com/article/businessNews/idARAKBN1F82ET [accessed in June 2018]

Ashrae 2013a “Fenestration” *ASHRAE Handbook of Fundamentals* (USA: Ashrae) p 15.1-15.62

Ashrae 2013b “Nonresidential Cooling and Heating” *Ashrae Handbook—Fundamentals* (USA: Ashrae) p 18.1-18.57

Bagdanavicius A, Jenkins N and Hammond P G 2012 “Assessment of community energy supply systems using energy, exergy and exergoeconomic analysis” *Energy* **45** 247–55

Bali T and Sarac B 2008 “Exergy analysis of heat transfer in a turbulent pipe flow by a decaying swirl generator” *Int. J. Exergy* **5** 64–77 Online: http://www.inderscienceonline.com/doi/abs/10.1504/IJEX.2008.016013

Balta M T, Dincer I and Hepbasli A 2010 “Performance and sustainability assessment of energy options for building HVAC applications” *Energy Build.* **42** 1320–8

Bejan A 2002 “Fundamentals of exergy analysis, entropy generation minimization, and the generation of low architecture” *Int. J. Energy Res.* **26** 545–65

Bicer Y and Dincer I 2016 “Analysis and performance evaluation of a renewable energy based multigeneration system” *Energy* **94** 623–32

Biserni C and Garai M 2015 "First and second law analysis applied to building envelope: A theoretical approach on the potentiality of Bejan’s theory" *Energy Reports* **1** 181–3

Boonassa S, Namprakai P and Muangnapoh T 2006 Performance improvement of the combined cycle power plant by intake air cooling using an absorption chiller *Energy* **31** 2036–46 Online: http://www.sciencedirect.com/science/article/pii/S0360544205001842%5Cnhttp://linkinghub.elsevier.com/retrieve/pii/S0360544205001842

BP Energy Economics 2018 *“BP Energy Outlook 2018 Edition”*

Caliskan H 2016 “Low-Exergy Analysis of a Building with Aground Source Heat Pump” *IJEECS* **5** 15–25

Caliskan H, Dincer I and Hepbasli A 2012 “Exergoeconomic , enviroeconomic and sustainability analyses of a novel air cooler” *Energy Build.* **55** 747–56 Online: http://dx.doi.org/10.1016/j.enbuild.2012.03.024

Cassetti G, Rocco M and Colombo E 2013 Exergy based methods for economic and environmental design optimization of energy systems *Proc. 26th Int. Conf. Effic. Cost, Optim. Simul. Environ. Impact Energy Syst.*

Çengel Y A and Boles M A 2011 *“Thermodynamic An Engineering Approach”* (Singapore: Mc Graw-Hill)

Cervigni R, Rogers J A and Dvorak I 2013 *A WORLD BANK STUDY Assessing Low-Carbon Development in Nigeria :An Analysis of Four Sectors* (Washington, DC: World Bank)

Compton, M. and Rezaie B 2017 “Enviro-exergy sustainability analysis of boiler evolution in district energy system” *Energy* **119** 257–65

Dincer I and and Rosen M A 2000 *“Exergy Energy, Environment and Sustainble Development”* (San Diego, CA 92101-4495, USA: Elsiver Ltd.)

Dincer I and Rosen M A 2012 *Exergy: Energy, Environment and Sustainable Development* (Oxford.: Elsevier Science)

Gedso S and Petersen A J 2016 Heating and Cooling Simulation using BIM in Norway *CLIMA 2016 - proceedings of the 12th REHVA World Congress* (Aalborg: Aalborg University, Department of Civil Engineering) Online: http://vbn.aau.dk/files/233778874/paper_753.pdf

Gonçalves P 2013 *Energy and exergy assessments for an enhanced use of energy in buildings* (Coimbra)

Greenhouse Gas Reporting Program (GHGRP) 2017 Greenhouse Gas Reporting Program Data *United States Environ. Prot. Agency* Online: https://www.epa.gov/ghgreporting/ghg-reporting-program-data-sets

Gros D and Roth F 2012 “THE EUROPE 2020 STRATEGY” 1–111 Online: www.ceps.eu

Gundersen T 2009 An Introduction to the Concept of Exergy and Energy Quality *Energy Process Eng.* **3** 1–25

Hepbasli A 2012 “Low exergy heating and cooling systems for sustainable buildings and societies” *Renew. Sustain. Energy Rev.* **16** 73–104

Ibrahim N and Kennedy C 2016 “A Methodology for Constructing Marginal Abatement Cost Curves for Climate Action in Cities” *Energies* **9** 1–17

Jansen S C, Teres-Zubiaga J and Luscuere P G 2012 “The exergy approach for evaluating and developing an energy system for a social dwelling” *Energy Build.* **55** 693–703

Kesicki F 2011 “Marginal Abatement Cost Curves for Policy Making – Expert-based vs. Model-drived curves” *33rd IAEE International Conference* (Rio de Janeiro, Brazil) pp 1–19

Kesicki F and Ekins P 2012 Marginal abatement cost curves: a call for caution *Clim. Policy* **12** 219–36 Online: https://doi.org/10.1080/14693062.2011.582347

Kevin S, Kuo L and Chou K 2016 “The applicability of marginal abatement cost approach : A comprehensive review” *J. Clean. Prod.* **127** 59–71 Online: http://dx.doi.org/10.1016/j.jclepro.2016.04.013

Kossoy A and Peszko G 2015 *“State and Trends of Carbon Pricing”* (Washington, DC 20433 USA)

Lohani S P 2010 Energy and exergy analysis of fossil plant and heat pump building heating system at two different dead-state temperatures *Energy* **35** 3323–31

Lorenzo M and 2014 Thermal Exergy analysis of a building *Energy Procedia 62 (2014) 723 – 732*

Lozano M A and Valero A 1993 “Theory of the exergetic cost” *Energy* **18** 939–60

Mahlia T M I, Taufiq B N, Ong K P and Saidur R 2011 “Exergy analysis for day lighting, electric lighting and space cooling systems for a room space in a tropical climate” *Energy Build.* **43** 1676–84

Mahmoudi S M S and Kordlar M A 2018 A new flexible geothermal based cogeneration system producing power and refrigeration *Renew. Energy* **123** 499–512

Al Moussawi H, Fardoun F and Louahlia-Gualous H 2016 Review of tri-generation technologies: Design evaluation, optimization, decision-making, and selection approach *Energy Convers. Manag.* **120** 157–96 Online: http://dx.doi.org/10.1016/j.enconman.2016.04.085

Myers D R 2013 *“Solar Radiation: Practical Modeling for Renewable Energy Applications”* ed A Ghassemi (Boca Raton, London, New York: CRC Press Taylor & Francis Group)

NEED 4B 2018 “New Energy Efficient Design for Building” *Eur. Union FP7 Proj. Cent. Energy, Environ. Econ. Ozeygin Univ. Proj. Rep.* 1–6

Nurdan Y and Hepbasli A 2014 Exergetic and Sustainability Evaluation of a Building Heating System in Izmir, Turkey *Int. J. Civil, Environ. Struct. Constr. Archit. Eng.* **8** 1003–11 Online: http://waset.org/Publications?p=93

Paniagua I L, Martin J R, Fernandez C G, Alvaro A J and Carlier R N 2013 “A New Simple Method for Estimating Exergy Destruction in Heat Exchangers” *Entropy* **15** 474–89

Pons M 2009 “On the Reference State for Exergy when Ambient Temperature Fluctuates” *Int. J. Thermodyn.* **12** 113–21 Online: www.icatweb.org/journal.htm

Rosen M A and Dincer I 2003 Exergy–cost–energy–mass analysis of thermal systems and processes *Energy Convers. Manag.* **44** 1633–51 Online: http://www.sciencedirect.com/science/article/pii/S0196890402001796

Sakulpipatsin P 2008 *“Exergy Efficient Building Design”* (University of Applied Sciences Offenburg geboren te Suphan Buri, Thailand)

Sakulpipatsin P, Itard L C M, van der Kooi H J, Boelman E C and Luscuere P G 2010 An exergy application for analysis of buildings and HVAC systems *Energy Build.* **42** 90–9

Schmidt D 2004a “Design of Low Exergy Buildings - Method and Pre-Design Tool” *Int. J. Low Energy Sustain. Build.* 1–47

Schmidt D 2009 “Low exergy systems for high-performance buildings and communities” *Energy Build.* **41** 331–6

Schmidt D 2004b “New ways for energy systems in sustainable buildings” *21st Conf. Passiv. Low Energy Archit. Eindhoven, Netherlands* 1–6

Schmidt D and Ala-Juusela M 2004 “Low Exergy Systems for Heating and Cooling of Buildings” *21st Conf. Passiv. Low Energy Archit.* **21** 19–22

Sevilgen S H and Sancar O 2011 “Economical analysis of trigeneration system” *Int. J. Phys. Sci.* **6** 1068–73

Sibilio S, Rosato A, Ciampi G, Scorpio M and Akisawa A 2017 Building-integrated trigeneration system: Energy, environmental and economic dynamic performance assessment for Italian residential applications *Renew. Sustain. Energy Rev.* **68** 920–33 Online: http://dx.doi.org/10.1016/j.rser.2016.02.011

Teres-Zubiaga J, Jansen S C, Luscuere P and Sala J M 2013 "Dynamic exergy analysis of energy systems for a social dwelling and exergy based system improvement" *Energy Build.* **64** 359–71

Tian W 2013 A review of sensitivity analysis methods in building energy analysis *Renew. Sustain. Energy Rev.* **20** 411–9 Online: http://linkinghub.elsevier.com/retrieve/pii/S1364032112007101

Timilsina G R, Sikharulidze A, Karapoghosyan E and Shatvoryan S 2017 "Development of marginal abatement cost curves for the building sector in Armenia and Georgia" *Energy Policy* **108** 29–43 Online: http://dx.doi.org/10.1016/j.enpol.2017.05.041

Tomaschek J 2015 Marginal abatement cost curves for policy recommendation – A method for energy system analysis *Energy Policy* **85** 376–85 Online: http://www.sciencedirect.com/science/article/pii/S0301421515002141

Torio H and Schmidt D 2011 *"Low Exergy System for Hight-Performance Building and Communities"* (Germany)

Torio H and Schmidt D 2007 "More sustainable buildings through exergy analysis Solar thermal and/or ventilation systems" *Energy* Online: http://publica.fraunhofer.de/starweb/servlet.starweb?path=pub0.web&search=N-76632

Tsatsaronis G 2007 "Definitions and nomenclature in exergy analysis and exergoeconomics" *Energy* **32** 249–53

Tsatsaronis G and Morosuk T 2012 "Understanding and improving energy conversion systems with the aid of exergy–based methods" *Int. J. Exergy* **11** 518–42

Tsatsaronis G, Morosuk T, Koch D and Sorgenfrei M 2013 "Understanding the thermodynamic inefficiencies in combustion processes" *Energy* **62** 3–11

Turkish Statistical Institute 2017 Electricity and N-G prices.[online]

http://www.turkstat.goc.tr/PreHaberBlultenleri.do? id=24637/ (accessed 19 September 2017). *Press Release* Online: http://www.turkstat.gov.tr/PreHaberBultenleri.do?id=24637

Wächter P 2013 "The usefulness of marginal CO2-e abatement cost curves in Austria" *Energy Policy* **61** 1116–26 Online: http://dx.doi.org/10.1016/j.enpol.2013.06.125

WBCSD 2009 "Energy Efficiency in Buildings - Transforming the Market" 1–77

Website Electricity CO2 emission [online] https://www.sunearthtools.com-tools-CO2-emissions-calculator.php/ (accessed 2 Augest 2017).

Wei Z and Zmeureanu R 2009 "Exergy analysis of variable air volume systems for an office building" *Energy Convers. Manag.* **50** 387–92

Whyte J, Lindkvist C, Jaradat S and Ibrahim N H 2012 *"Guidelines on Carbon Emission of Products and Services"* (London Organising Committee of the Olympic and Paralympic Games(LOCOG))

Wierciński Z and Aldona S-S 2012 Energy and Exergy Flow Balances for Traditional and Passive Detached Houses *Tech. Sci.* **15** 15–33

Winterbone D E and Turan A 2015 Advanced Thermodynamics for Engineers (Butterworth-Heinemann) pp 13–33

Xiao H, Wei Q and Wang H 2014 "Marginal abatement cost and carbon reduction potential outlook of key energy ef fi ciency technologies in China ' s building sector to 2030" *Energy Policy* **69** 92–105 Online: http://dx.doi.org/10.1016/j.enpol.2014.02.021

Yildiz A and Güngör A 2009 "Energy and exergy analyses of space heating in buildings" *Appl. Energy* **86** 1939–48 Online: http://dx.doi.org/10.1016/j.apenergy.2008.12.010

Yucer C T and Hepbasli A 2013 Exergoeconomic analyses of an energy supply chain for space heating in a building *Energy Build.* **62** 343–9

Yücer C T and Hepbasli A 2014 "Exergoeconomic and enviroeconomic analyses of a building heating system using SPECO and Lowex methods" *Energy Build.* **73** 1–6

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