ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A NEW APPROACH TO DEFINE ECONOMICALLY APPLICABLE ENERGY EFFICIENT RETROFIT SOLUTIONS FOR RESIDENTIAL BUILDINGS IN TURKEY

PhD THESIS

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Department of Architecture

Building Science Programme

JULY 2016

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Programı : Herhangi Program

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TÜRKİYE'DEKİ KONUT BİNALARININ ENERJİ ETKİN İYİLEŞTİRMESİ İÇİN EKONOMİK OLARAK UYGULANABİLİR ÇÖZÜMLERİN BELİRLENMESİNDE YENİ BİR YAKLAŞIM

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TEMMUZ 2016

Touraj ASHRAFIAN, a **Ph.D.** student of ITU **Graduate School of Science, Engineering and Technology** student ID **502112064**, successfully defended the **thesis/dissertation** entitled "**A NEW APPROACH TO DEFINE ECONOMICALLY APPLICABLE ENERGY EFFICIENT RETROFIT SOLUTIONS FOR RESIDENTIAL BUILDINGS IN TURKEY**", which he prepared after fulfilling the requirements specified in the associated legislations.

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To my spouse,

FOREWORD

Since June 2011, I have been conducting my Ph.D. study on the buildings' energy efficient retrofitting. I have concluded some conference papers and a journal paper related to the topic during this period. I involved in a TÜBİTAK supported project that provides a base for my study and a ministerial supported project related to the topic. I have experienced this period as fascinating and instructive. The fund from the Scientific Research Projects' Unit (BAP) of Istanbul Technical University helped me to conduct the investigation.

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July 2016

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ABBREVIATIONS

ACH : Air Change per Hour
Acr. : Acronym
ASHRAE : American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEP-TR : National Building Energy Performance Calculation Methodology of Turkey
BPIE : Buildings Performance Institute Europe
CFL : Compact Fluorescent
CO_2 : Carbon Dioxide
COP : Coefficient of Performance
DHW : Domestic Hot Water
DOE : Department of Energy of United State of America
EPBD : Energy Performance of Buildings Directive
EP : Energy Performance
EPC : Energy Performance Certificate
EPS : Expanded Polystyrene
ERCM : Economically Reasonable Combined Measure except lighting improvements and renewable system applications
EU : European Union
G.C. : Global Cost
HVAC : Heating, Ventilation, and Air Conditioning
IEA : International Energy Agency
LED : Light-emitting Diode
Lux : Luminous Flux
MS : Member States
n.a. : Not Applicable
NPV : Net Present Value
nZEB : Nearly Zero Energy Building
PEC : Primary Energy Consumption
PV : Photovoltaic
RBs : Reference Buildings
SHGC : Solar Heat Gain Coefficient
TL : Turkish Lira
TS : Turkish Standard
TÜBİTAK : The Scientific and Technological Research Council of Turkey
TÜİK : Turkish Statistical Institute
Tvis : Visible Transmittance
U-value : Heat Transfer Coefficient
U.S. : United State of America
v.s : Versus
Yr : Year

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A NEW APPROACH TO DEFINE ECONOMICALLY APPLICABLE ENERGY EFFICIENT RETROFIT SOLUTIONS FOR RESIDENTIAL BUILDINGS IN TURKEY

SUMMARY

Technology becomes an impartible part of human life, but it provides some obstacles for humankind. Global warming arisen from incrementation of greenhouse gases emission is one of them. The building stock is one of the most greenhouse gas emitter sectors. This emission is because of energy consumption related to providing comfort conditions in the buildings and also equipment. In the era of technology, everything is going to develop rapidly. New approaches and developments in the field of buildings' technology and science are making progress every day. Most of the buildings are built to be alive to at least more than a half of a century. The existing buildings require adopting with this excessive progress. Thus, regular maintenance and repairs are inevitable. The EU regulations related to the energy performance of the buildings persist on the significant reduction of energy consumption in all new and existing buildings. Such a reduction requires a deep retrofit in existing buildings. Any maintenance and repair, or in the other word retrofit, require a budget that sometimes is a huge amount for owners to pay, so the financing of the retrofit actions is significantly important. Financial barriers are one of the main obstacles to increasing the yearly retrofit rate. Any solution for financial barriers can boost the retrofit rate significantly.

At the mean time, the amount of energy efficient retrofit rates across EU and Turkey are very lower than expectation. In is necessary to reach 3% yearly retrofit rate across EU to reach the 2020 goals but the current rate is about a half of the required rate. For existing buildings in Turkey, there are not many actions related to improving their energy performance. The most common renovation action is the implementation of insulation and of course, it is not sufficient, but it is the sole option that a financial solution exists for. The aim of this study is to encourage flat owners to involve in the retrofit action of their buildings as financiers. It causes to increase the amount of financial resources incomparably and thus increase the retrofit rate considerably. It would be applicable when the amount of payments for retrofit action is below the payable and reasonable amount. Based on some national statistics, this reasonable amount could be about 2270 TL in Turkey. Thus, applicable retrofit scenarios should have an investment cost lower than this amount. As this amount is calculated based on households' yearly income and expenditures, it is expected that this amount can be invested each year regularly. Hence, if any deep retrofit action can be divided into some steps that require a yearly payment lower than reasonable cost is an affordable and applicable action.

A methodology to define the applicable solutions are defined in the third section of the thesis. As the economic approach is the main focus of the study, the solutions that provide the lowest cost during the calculation period (so-called cost-optimal

solutions), are mostly focused. However, the similar methodology can be developed for other targets such as nearly zero energy buildings. This method is adopted from the recast version of Energy Performance of Buildings Directive of EU (EPBD-Recast) to define the cost-optimal retrofit solutions. The unique approach to set the step-by-step scenarios and their costs are defined at the following parts of the methodology section.

The fourth part of the study is belonged to the application of the methodology to some case study buildings. Two different case study buildings are selected to analyze. One of them is representing the detached housing system, and another one is representing the row housing system. It is supposed that these buildings were constructed in two different periods to make it possible to disseminate the results to the country level. The case study buildings are chosen from reference buildings that are defined for Turkey through a TÜBİTAK supported project conducted by the thesis advisor and writer as a group member. These reference buildings are analyzed in the three different climatic regions of Turkey. Antalya, Erzurum, and Istanbul are selected as representative cities for these climatic regions. The energy performance of these buildings in each climate is defined using dynamic simulation tools. Various retrofit measures are determined and applied to these building, and the energy performance of the existing buildings under retrofit by each of these measures are defined. The global cost for each existing building and retrofit measures are calculated, and the global cost vs. primary energy consumption graph as indicated by EPBD-Recast are drawn. The lowest point of the graph which is indicating the cost-optimal measures are determined. The cost per flat is calculated in the following. As all of the optimal measures required to a higher payment than a reasonable amount of payment, all actions had analyzed under step-by-step retrofit. The results are illustrating that the energy and cost performance of the existing buildings under retrofit by instant and step-by-step scenarios contains negligible differences. The sensitivity analyses for different economic variations are undertaken as well to define the influence of economic variations on the results of the study.

The fifth section of the study is belonged to the discussion and analyses of the results. In this section, the results of the cost and energy analyses of each building located in the different climatic region are compared with each other. The results are indicating that the retrofit actions in cold climates have a priority to the actions in other climates. Also, the results reveal that step-by-step retrofit provides at least 67.19 kWh/m^2 primary energy saving per year. While the minimum global cost and CO_2 emission savings are 103.8 TL/m^2 and 16.62 Kg/m^2.a respectively. In the country level, 56,569 GWh primary energy could be saved by application of step-by-step scenarios. At the same time, 13,992,985 Tons of CO_2 emission will be prevented yearly. The global cost will be reduced by 87393 million TL in 30 years. So, the application of step-by-step scenarios will lead to 2913 million TL yearly direct profit for the country.

The last section of the study is providing some recommendation for future works together with the conclusion of the study.

TÜRKİYE'DEKİ KONUT BİNALARININ ENERJİ ETKİN İYİLEŞTİRMESİ İÇİN EKONOMİK OLARAK UYGULANABİLİR ÇÖZÜMLERİN BELİRLENMESİNDE YENİ BİR YAKLAŞIM

ÖZET

Hızlı bir kentleşme süreci yaşadığımız son zamanlarda teknoloji, insan hayatının bir ayrılmaz parçası haline gelmiştir, fakat bu durum insanlık için bazı problemler oluşturmaktadır. Sera gazları salımı artışından kaynaklanan küresel ısınma sözü geçen problemler arasında en önemlilerden birisidir. Binalar dünyadaki toplam sera gazı salımının en az 1/3'ünden sorumludur. Bu salımın nedeni, bina içinde kullanıcıların konfor koşullarını sağlamak için kurulan sistemler ve ayrıca içeride kullanılan diğer ekipmanların enerji tüketimidir.

Yaşam ömürleri uzun olan binalar ülkedeki enerji tüketiminin büyük bir bölümden sorumludur. Dolaysı ile sera gazı salımının çoğunluğundan sorumlu olan binaların enerji performansının iyileştirilmesi AB komisyonunun da vurguladığı gibi hem yeni hemde mevcut binalarda önemli bir konu olmaktadır. Binalarda enerji verimliliği ve bu konuda yapılan yatırımlar için ekonomik kaynakların doğru kullanımını amaçlayan çalışmalar başta Avrupa Birliği (AB) olmak üzere tüm dünyada önem kazanmıştır ve hızla devam etmektedir. Mevcut binalarda enerji performanslarını yeterli miktarda iyileştirmek için çok kapsamlı veya AB komisiyonunun ifadesi gibi derin iyileştirme (deep retrofit) önlemleri ele alınmalıdır. Kapsamlı iyileştirme önlemleri, bina sahipleri için büyük miktarda bir bütçe gerektirir, bu nedenle iyileştirme projelerinin finansmanı önem arz etmektedir. Finansal engeller iyileştirme oranını artırmak için ana engellerden biridir. Konut binaları söz kousu olduğunda, toplam bina stoğu içinde çok sayıda konutun bulunması nedeniyle konut binalarında yapılacak iyileştirme çalışmaları ülkenin sera gazı salımlarının azaltılmasında büyük bir paya sahiptir. Ancak konut binalarının iyileştirmesinde konut sahipleri aynı zamanda yatırımcılardır. Bu nedenle konut binalarının iyileştirilmesindeki ekonomik bariyerler inovatif finansal çözümlerle desteklenmesi gereken çok önemli bir konudur. Eğer daire sahiplerinin kendi projeleri için ödeyecekleri miktar onların gelirlerine oranla ödeyebileceği makul bir miktar olursa projenin sağladığı yararlar onları projeye katılmak için ikna edebilir. Ancak sağlanan çok yararlara rağmen iyileştirme projelerin sayısının az olması daire sahiplerinin bu tür projelere ikna olmamalarının bir göstergesidir. Bu tezdeki araştırma, konusu geçen sorunu çözmek için yeni bir yaklaşım sunmaktadır. Bu yaklaşımın uygulanması sonucunda, enerjinin verimli kullanılması ile enerjide dışa bağımlılığın azaltılması, bunun sonucunda da binaların uzun dönem maliyetlerinin düşmesi bu çalışmanın yararlarındandır.

Avrupa Birliği'nde, binaların enerji performansını değerlendirmek, sertifikalandırmak ve bu yolla enerji verimliliğini arttrmak amacıyla 2002 tarihli "Binalarda Enerji Performansı Direktifi" (EPBD) yayınlanmıştır. AB yasaları uyum sürecinde Türkiye'de de, 2008 yılında yayınlanan "Binalarda Enerji Performansı Yönetmeliği" ile tüm binalara BEP-TR hesaplama yöntemi kullanılarak enerji kimlik belgesi

verilmesi zorunlu olmuştur. Türkiye'deki bu süreç içerisinde AB ülkelerinde yeni gelişmeler yaşanmış ve EPBD'nin revize edilmesiyle 2010 yılında yürürlüğe giren yeni direktif (EPBD-Recast) kapsamında "maliyet optimum enerji verimliliği" kavramı ortaya konulmuştur. Bu revize direktif ile tüm Avrupa ülkelerine binalarda maliyet optimum enerji verimliliği seviyelerini hesaplama zorunluluğu getirilmiştir. Bu hesaplamaların, Ocak 2012'de Avrupa Komisyonu tarafından yayınlanan yönetmelikteki çerçeve yönteme uygun olarak geliştirilen ulusal yöntem kullanılarak yapılması gerekmektedir. Ayrıca, mevcut bina stoğu dikkate alındığında, binalarda maliyet optimum enerji verimliliği seviyesi hesabının her bir bina için ayrı ayrı yapılamayacağı açıktır. Bu nedenle, hem mevcut hem de yeni yapılacak binaları en iyi düzeyde temsil edebilecek referans binaların belirlenmesi EPBD Recast 2010'un da öngördüğü gibi zorunlu olmuştur.

AB ve Türkiye genelinde enerji verimliliği iyileştirme oranı beklentiden çok daha düşüktür. AB 2020 hedefleri ulaşmak için AB ülkelerinde binaların yılda 3%'ü iyileştirilmelidir ancak mevcut durumda sadece binaların yılda 1.5% iyileştiriliyor. Türkiye'de de çoğunlukla bina kabuğunda yapılan ısı yalıtımı ile yüksek enerji tüketimine karşı önlemler alınmaya çalışılmaktadır. Ancak, Avrupa Birliği Binalarda Enerji Performans Direktifi'nin (EPBD) de şart koştuğu gibi, sadece yalıtım malzemelerinden yararlanılması değil bina kabuğu ve bina alt sistemlerinde yapılacak çeşitli uygulamalar ile yenilenebilir enerji kaynaklarından da verimli bir şekilde yararlanılması ve bu yolla karbon salımlarının azaltılması öngörülmektedir. Ancak sadece yalıtım uygulaması için mevcut olan finansal çözüm binalardan elde edilmesi gereken enerji tasarrufunu sağlamamaktadır.

Bu çalışmanın amacı, konut binalarında daire ve bina sahiplerini enerji verimli iyileştirmelerde finansörler olarak projeye katılmalarını teşvik etmektir. Daire sahiplerinin iyileştirme projeleri için ödemeleri gereken tutar ödeyebilecekleri makul tutarın altında olması gerekmektedir. Ulusal istatistiklere dayanarak ve gelir düzeyi de düşünülerek, bu makul miktar yaklaşık 2270 TL olarak belirlenebilir. Bu miktar, hanehalkının yıllık gelir ve harcamaları esas alınarak hesaplanmıştır. Bu miktar düzenli olarak her yıl daire sahipleri tarafından yatırım yapilabilecek miktar olarak kabul edilebilir. Bu nedenle, eğer yüksek ilk yatırım maliyeti gerektiren derin iyileştirme önlemlerini daha düşük ve makul bir yıllık ödeme gerektiren adım adım iyileştirme ile yapılabilirse o zaman bu derin iyileştirme önlemi uygulanabilir bir önlem olabilir.

Türkiye'de son yıllarda binalarda temiz ve yenilenebilir enerji kullanımı ve enerji verimliliği konularında yapılan faaliyetler her ne kadar da artış gösterse bile yine de enerji tüketimi çok düşüş göstermemektedir ve bu da bu faaliyetlerin yeterli ve ya doğru yönde olmadığını göstermektedir. Enerji tüketiminin önemli ölçüde azaltılması gelişmekte olan ülke ekonomisine finansal anlamda katkı sağlayacağı gibi tasarrufların yatırıma dönüştürülmesi halinde ülkenin önemli sorunlarından biri olan işsizlik için yeni istihdam alanları açılmasına da olanak sağlayarak sorunun çözümüne katkı sağlayacaktır.

AB komisyonunun yayınladığı yönetmelikler ile tanımlanmış olan "maliyet optimum" ve "yaklaşık sıfır enerji" binalar terimleri giderek yaygınlaşmaktadır ve her AB ülkesi ve aday ülkeler bu tanımları kendi ülke koşullarına göre tanımlamaya başlamışlardır. Ancak bir çoğu AB ülke ve aday ülkenin aksine Türkiye'de henüz bu konuda gerekli sayıda ve nitelikte çalışma gözükmemektedir.

EPBD-Recast kapsamında binalarda maliyet optimum enerji verimliliği seviyesine ulaşmak için kullanılacak yöntemde izlenecek ana adımlar aşağıdaki gibidir:

- Referans binaların belirlenmesi,
- Enerji verimliliği tedbirlerinin belirlenmesi,
- Birincil enerji ihtiyacının hesaplanması,
- Toplam maliyetlerin hesaplanması,
- Analizlerde kullanılan verilere ilişkin duyarlılık analizlerinin yapılması,
- Referans binalar için maliyet optimum enerji verimliliği seviyelerinin belirlenmesidir.

Çalışma kapsamındaki temel faaliyetleri beş ana bölüme ayrılır. Birinci ana bölüm tezin amacı ve hedeflerini açıklamaktadır. İkinci bölüm litratür taramasını kapsamaktadır.

Uygulanabilir çözümleri tanımlamak ve ilgili hesapları yapmak için gerekli yöntem tezin üçüncü bölümünde açıklanmaktadır. Bu yöntem, hesaplama döneminde en düşük global maliyet gerektiren (optimum maliyet) çözümleri bulmaya yönelik bir yöntemdir. Ancak benzer bir yaklaşım yaklaşık sıfır enerji binalar gibi farklı hedefler için de geliştirilebilir. Bu yaklaşım adım adım iyileştirme senaryoları tanımlamak ve bunların maliyetlerini hesaplamak için yeni bir yöntemde sunmaktadır. Bu yöntem, AB'nin Bina Enerji Performansı Direktifi'nin (EPBD-Revize) maliyet-optimal çözümleri tanımlamak için yayınlanan sürümününden türetilmiştir.

Çalışmanın dördüncü bölümü, üçüncü bölümde anlatılan yöntemin uygulanmasına aittir. İki farklı örnek bina analiz için ele alınmıştır. Bunlardan biri ayrık nizam konut sistemini temsil eder ve diğeri bitişik nizam sistemi temsil etmektedir. Ülke bazında doğru sonuçlar elde etmek için seçilen binaların farklı dönemlerde ve farklı iklim koşulları altında inşa edildiği kabul edilmiştir. Seçilen binalar, TÜBİTAK tarafından desteklenen bir araştırma projesi tarafından Türkiye için tanımlanan referans binalarından seçilmiştir. Bu referans binaları Türkiye'nin üç farklı iklim bölgesinde analiz edilmiş olup Antalya, Erzurum ve İstanbul bu iklim bölgelerini temsil eden şehirler olarak seçilmiştir. Bu binaların her iklimde ayrı ayrı enerji performansları ile birlikte yıllık ısıtma, soğutma, havalandırma, sıhhi sıcak su ve aydınlatma enerji ihtiyaçları detaylı dinamik simülasyon araçları kullanılarak hesaplandıktan sonra, CO_2 salım miktarları da CO_2 dönüşüm katsayıları kullanılarak hesaplanmıştır. Çeşitli iyileştirme tedbirleri/tedbir paketleri belirlenme ve mevcut binaların modellerine entegre edilmiştir. Tanımlanan bu tedbirler ile iyileştirilmiş mevcut binaların enerji performansı seviyeleri hesaplanmıştır. Bu tedbirler gerekli bina tipolojisine, iklime, ve ulusal ekonomik koşullara uygunluğu değerlendirilerek belirlenmiştir, ayrıca piyasadaki genel eğilim de dikkate alımıştır. Yenilenebilir enerji kullanımı ile ilgili tedbirler de bu kapsamdaki analizlere dahil edilmiştir. Her mevcut bina ve iyileştirme önlemlerinin uzun dönem (global) maliyeti ve birincil enerji tüketimi hesaplandıktan sonra, en düşük ekonomik yaşam dönemi maliyeti veren iyileştirme tedbiri (önlemi) maliyet optimum önlemi gösterir. Her daire için ilk yatırım maliyeti makul miktarda olan maliyet optimum önlemler uygulamaya alınabilir ancak bu çalışmada tüm maliyet optimum önlemler daha yüksek ödeme gerektirdiği için tüm bu önlemler adım adım iyileştirme altında analiz edilmiştir. Tek adımda ve adım adım senaryolar ile iyileştirme yapılan mevcut binaların enerji performansları ve uzun dönem maliyetleri karşılaştırılmıştır. Ayrıca, farklı ekonomik değerler ile yapılan duyarlılık analizi

sonuçunda ekonomik değişkenlerin çalışma sonuçları üzerinde olan etkisi de araştırılmıştır.

Çalışmanın beşinci bölümünde tartışma ve sonuçların analizleri yer almaktadır. Bu bölümde, farklı iklim bölgelerinde her binanın 30 yıllık uzun dönem maliyeti veya bir başka ifadede global maliyeti ve enerji analiz sonuçları birbirleri ile karşılaştırılmıştır. Sonuçlar soğuk iklimde iyileştirme projelerini diğer iklimlere göre daha öncelikli olduğunu göstermektedir. Tüm analizler sonucunda adım adım iyileştirme uygulamsı ile yıllık en az 67.19 kWh/m^2a birincil enerji tasarrufu sağlanabileceğini ortaya koymaktadır. Aynı zamanda en az global maliyet ve yıllık CO_2 salımı tasarrufu sırasıyla 103.8 TL/m^2a ve 16.62 kg/m^2a dir. Tez çalışmasında örnek olarak alınan binaların yer aldığı zaman aralığında yapılan tüm konut binalarının sayısını göz önüne alındığında adım adım iyileştirme senaryoları ile 56569 GWh birincil enerji tasarrufu potansiyeli olduğu saptanmıştır. Bu önlemlerle yılda 13.992.985 Ton CO_2 salımını azaltma potansiyeli bulunmaktadır. Böylece, adım-adım senaryolarının uygulaması ülke için yılda 2,913,000,000 TL'lik toplam maliyet tasarruf potansiyeli bulunmaktadır.

Çalışmanın son bölümünde çalışmanın genel değerlendirmesi ile birlikte konu ile ilgili gelecekteki çalışmalr için bazı öneriler öngörülmektedir.

1. INTRODUCTION

Fuel shortage and huge amount of energy consumption in building sector that are important reasons for climate change, is leading society to create legislations and obligate building owners to retrofit their buildings and increase the energy performance of them. Following the European Union's directive 2002/91/EC, there is an increasing focus on building's energy certification and reducing energy consumption and carbon dioxide emission of the building sector in EU. Currently about 40% of the EU's energy consumption and carbon dioxide emissions come from the way that buildings are lit, heated, cooled and ventilated. Number of existing building is very much in comparison with new buildings that would be built in a year. About 75% of whole buildings' floor spaces belongs to residential buildings in EU and they are account for 27% of total final energy consumption that is about 68% of energy consumption of building stock. (BPIE, 2011) In European cities, three-quarters of the building stock that will exist in 2050 already exists today. (Lewis et al, 2013) In EU approximately 35% of buildings have more than 50 years old. (Desogus et al, 2013) Thus, the existing building stock is very important to be energy efficient. Yet, there is a significant potential for improving energy efficiency through deep renovation of the buildings and by doing so reducing energy consumption with cost-effective measures. Without doubt, even comparatively small changes in energy performance and the way we operate building can have a significant effect in reducing total energy consumption and cost.

Building energy performance does not only affect energy consumption and cost component, but also influences the greenhouse gas emissions, occupants' health and productivity, property value, poverty level and the business bottom line. Recent investigations in the buildings' energy performance field illustrate that energy efficient deep renovation of the existing building stock provides a high amount of direct benefits from energy saving point of view while it can provide many indirect benefits for society such as falling unemployment level and rising living standard as well. They have shown that the energy savings from building energy retrofit projects can offer the

potential for strong financial returns while it differs from country to country and depends on conditions but in general, it provide huge financial benefits for every country. However, when we consider a building and look at the comeback period and barriers of every retrofit project, it seems a little irrational as its benefit is not convincing for owners. That is why there is less contribution demand among building's owner and occupants to retrofit their buildings. Recent financial crises are another reason for this barrier. By conducting a detailed analysis, the related risks can be reduced significantly. In the scale of a country, it is entirely rational, and there are so convincing benefits. In the larger scales, properly designed energy efficient retrofits provide new job offers, reduction in greenhouse gas emission, an increase in Gross Domestic Product (GDP), reduce the dependency of the country and reduce the amount of product import. For instance, a research has been illustrated that deep renovation program in Hungary could create by 2020 up to 131,000 net new jobs also it is highlighted that up to 38% of the employment gains are due to the indirect effects on other sectors that supply the construction industry and the induced effects from the increased spending power of higher employment levels. (Ürge-Vorsatz et al., 2010) However, the main problem is that when owners compare the cost benefits of the related project with investment cost and consider risks of long period comebacks they prefer not to involve in the project, hence, it is important to pay enough attention to encourage them to join in the actions. Even long-term mortgage and sometimes well-organized educational programs cannot be very effective as still there are lots of risks. Presenting more realistic and tangible results to them can be more efficient. The second option is to pay most of the investment cost by public authorities from the saved budget that will provide for the country by doing such a project in large scale. A detailed cost analysis is necessary for each two options. On the other hand, cost analysis plays an important role in not only defining an efficient method for energy retrofit of existing buildings, but also for encouraging owners to join in. Without detailed cost analysis it is impossible to make a feasible decision and choose an appropriate measure among variety of available retrofit measures, also, it is obvious that presenting a detailed analysis contains the comeback period can be more efficient than any other methods like long-term mortgages and educational programs to encourage owners to join in an energy efficient retrofit program. Also to obtain realistic result, it is necessary to have sensitivity analysis mostly for economic parameters.

By considering the magnitude of existing buildings stock, it will be obvious that it is not rational to analysis cost for each building separately. In the other words, from policy making point of view, critical cost analysis should be done for a large number of building to be efficient and to make large-scale decisions. Thus, building categorization and Reference Buildings establishment is inevitable.

To provide society with a huge amount of retrofit actions, it is necessary to create packages that have low investment cost and improve the energy efficiency of buildings in considerable amount. Indeed, packages and measures that contain high technology can be applied to a few buildings due to high investment cost. However, they can improve the energy efficiency of buildings more than others; they cannot provide society with so many economic benefits.

Also, it persisted by SEC 277 (2011) of European that residential and services or tertiary sectors, which mainly include building sector, offer the biggest savings potential from the final energy sectors. According to that document, only 22% of the total energy consumption in the service sector is to be attributed to the use of electric appliances and lighting while in the residential sector it is 12%. This means that by considering macroeconomic circumstances during the renovation of buildings more attentions should be paid to HVAC system than electrical energy consumption, and when to compare building types, in the service sector or public buildings the attention to electrical energy consumption should be more than residential sector.

To make more tangible and realistic result for related projects, the output data should be shifted from demand to the consumption. Thus, the user profile should be applied thoroughly and schedules should be organized accurately to the projects and also economic analysis should be done accurately. This is difficult for residential buildings as they contain lots of profiles and schedules; on the other hand, having the accurate result of the economic analysis is not so convenient.

While financing retrofit actions is a key obstacle in this field, scientists and decision makers are trying to develop high applicable methods that can satisfy owners to involve in the actions. Measures for retrofits contain packages with low, median and high initial investment cost; each of these packages' type has a special influence on number of the buildings that will go under retrofit. Not only low initial investment cost but also staged retrofit with even median and high investment cost can raise the number

of retrofit projects in society. What important about staged renovation is that distribution of retrofit actions to different period should decide accurately. Staged renovation can satisfy owners to involve in a retrofit action. While initial investment cost is in the lowest level and owners feel the result of renovation action in their real life, then they can accept other retrofit actions or even deep retrofits. The staged renovation is mentioned in recent Energy Efficiency Directive of EU (EU Parliament, 2012) and obligate MS to establish a long-term strategy for mobilizing investment in the renovation of the national stock of residential and commercial buildings encompass policies and measures to stimulate cost-effective deep renovations of buildings, including staged deep renovations.

The existing residential building sector is the least efficient building sector from energy performance point of view as the sector is less integrated with state of the art technologies. This results in a magnificent market potential. According to the World Business Council for Sustainable Development's investigation, multi-family buildings represent about half of the building stock in EU, where the majority of apartment buildings were constructed even before 1975. In Turkey, the situation is a little different, as the largest share of the Turkish buildings is constructed after 1970 according to building census from 2000, but with a lack of supervision and mandatory obligations, like building regulations, etc. Turkish standards related to energy efficiency have existed since 1985 while being not mandatory before the 2000s. As a result, also, in Turkey, there is a huge energy saving potential in the building sector especially in residential buildings where lack of awareness also is more noticeably.

In Turkey, buildings sector is responsible for the consumption of about 35% of total energy consumption and the building sector's emissions are 32% of the total national energy-related CO_2 emissions. "Experts predict the new regulation could create more than $30 billion in investment for energy efficiency solutions in homes. Turkey consumes 36% of all its energy through household utilities. Experts predict that with good housing insulation, the nation can save close to $10 billion annually. Turkey has 18.4 million homes according to 2008 statistics, and 10 million of these homes are located in big cities." (Liu F., et.al 2010) Based on these facts, it is clear that Energy Efficient Retrofit (EER) of existing residential buildings' stock in Turkey is inevitable and very beneficial.

This thesis study is one of pioneer studies in the implementation of EPBD-Recast in the Turkey and it is second study that focused on the Turkish residential buildings. The first study was a TUBİTAK supported research focused on the determination of the Turkish reference buildings and national cost-optimal level. This thesis study is introducing a new approach that used the amount of flat owners' investment costs to define the applicability of retrofit scenarios. In this way, step-by-step application of the retrofit measures is investigated thoroughly.

1.1 Purpose of Thesis

Deep retrofit actions are expensive, even if they are cost effective. Especially in the large scale applications, they require considerable up-front capital that is normally beyond the support of any single financial instrument. A great variety of financial instruments is available to support the energy performance improvement of buildings in the EU. Although there are lots of financing mechanism, the rate of building retrofit is still lower than anticipations. Rather than 3% retrofit rate yearly, the current rate is about 1.2% in most of EU countries. It will lead to the unsuccessful implementation of EU 2020 goals. To increase the yearly retrofit rate, it is necessary to encourage and convince owners to involve in the retrofit projects as a self-financier.

This thesis study is the first of its kind that focuses on the amount of money that should be paid by flat owners and investigate the step-by-step application of the retrofit scenarios. Particularly in the recent period, there are a lot of researches and studies focusing on the energy efficient retrofit of the building, but none of them are paying enough attention to the amount of investment by the users. It is estimated that failures in the increasing of the yearly retrofit rate are mostly due to requiring high investment amount and owners' reluctance to involve in the actions as financiers.

This research is aimed to provide a new approach for implementation of energy efficient retrofit in the existing residential building stock. Such an approach is focusing on the step-by-step application of the energy efficient retrofit solutions to make them economically applicable for existing residential building stock in Turkey. This will encourage flat owners to be self-financier for their retrofit projects. Also, it is proposed to present an approach to have more efficient retrofit projects. A detailed analysis of various parameters such as user profiles, economic variations and the impact of them on the retrofit project are included in the research. Besides, the methodology

framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements that were defined by supplementing document of EPBD-Recast 2010 is applied to Turkey's conditions. In general, this study has following aims:

- To illustrate a specific approach to step-by-step energy efficient retrofit based on Turkey's conditions for existing residential buildings,
- To present a methodology for applying to a huge amount of buildings with low initial investment cost,
- To encourage building owners and investors to involve in the retrofit actions as self-financiers,
- To define the criteria and methodology of step-by-step energy efficient retrofits of buildings.

1.2 Literature Review

As stated before, there aren't any research about the implementation of the step-by-step retrofit in the building. Also, there aren't any study focusing on the owners' investments to remove the financial barriers for required retrofit level in residential buildings. While, there are lots of investigations related to the other aspects of the energy efficient retrofit of the existing buildings. Thus, the literature review of the thesis is focusing on the researches and investigations in the field of energy efficient retrofit of the existing building.

In general, the literature of the subject was started from the energy obstacles araised from Arabian embargo in 1970's decade. A lots of regulations and studies were conducted after this period about buildings' energy performance, reference buildings and energy efficient retrofit. (Figure 1.1)

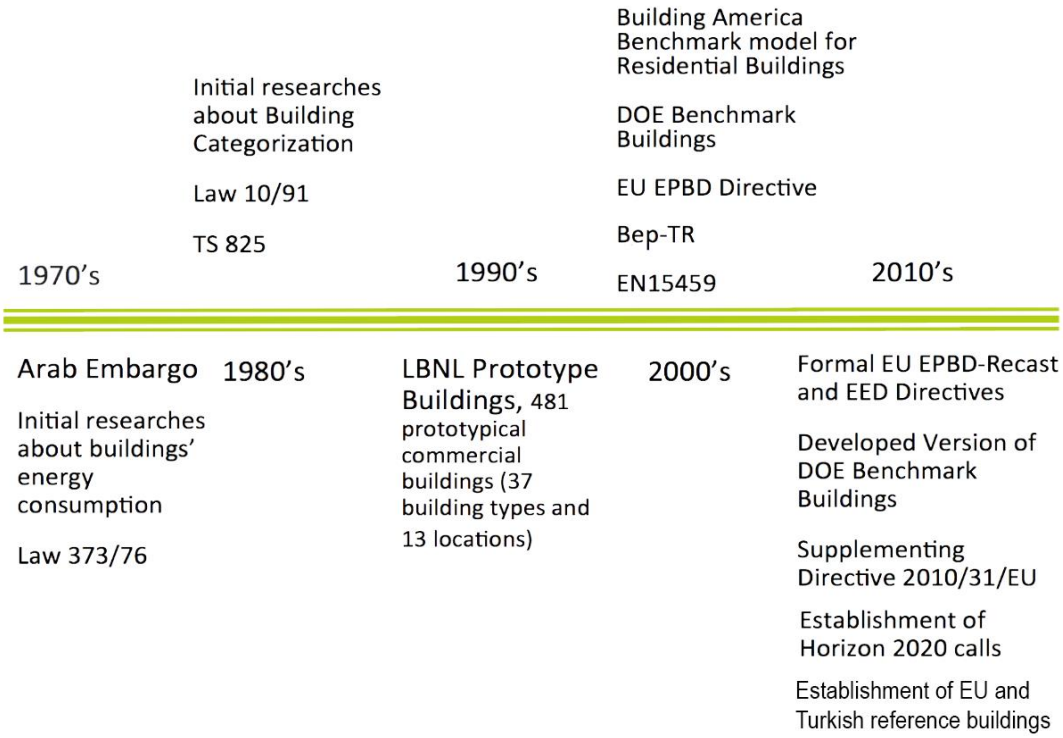

Figure 1.1: Development of the related literature during last decades.

1.2.1 State of the art related to energy performance regulations

The period between 1970 and 1990 belonged to the initial initiatives in the field of energy efficiency. In U.S., Energy Policy and Conservation Act (EPCA) (United States Congress, 1975) and ASHRAE Standard 90.1-Energy Conservation in New Building Design (ASHRAE, 1975) were published in 1975; in Italy first national energy saving legislation, law 373/76, (Bucci & Mollo, 2010) in UK, the building regulations no. 1676 (U.K. Parliament, 1976) and in Turkey, first building insulation related regulation was established in 1977 by Ministry of Energy and Natural Resources and then building standard related to energy efficiency and TS-825 were published in 1981 (Senkal Sezer, 2005). These legislations provide less energy efficiency than current legislations for building and as time goes on the legislations provide more restricted mandatory obligations for building stakeholders to obtain more energy efficiency in building stock. Hence, buildings that constructed according to related legislations require being retrofitted to reach enough energy efficiency. In EU, first Energy Performance Directive (EPBD-2002) obligated Member States (MS) to take measures to ensure that building with over 1000 m^2 floor area meets minimum energy performance requirements after major renovation (EU Parliament, 2002) and recast version of EPBD introduced cost-optimal level to the energy performance calculation

procedure, (EU Parliament, 2010) and also Energy Efficiency Directive persisted on energy efficient retrofit of existing building stock and encourage MS to increase the building renovation rate "as the existing building stock represents the single biggest potential sector for energy savings" (EU Parliament, 2012). One of EU 2050 goals is 80% energy consumption reduction in building sector in comparison with 2005 level which is only achievable if legislations be improved and the building energy retrofit rate increase by approximately 2% compare to current rate and receive to 3% per year up to 2020 ensure that all retrofits are deep or staged deep. This is equal to a huge number of retrofit projects. This will be achievable if the necessary financing mechanisms and market drivers can be provided. Horizon 2020 of EU is going to set activities to reach the mentioned goal. Moreover, it is stated that more ambitious action in energy efficiency will be needed to achieve EU objectives for 2030 (EU Parliament, 2013). The current renovation rate in EU is about 1.2%. Even if the 1.5% of buildings were being renovated incorporated the highest standards of energy efficiency, the European Union would miss its 20% energy saving targets for 2020. A closer look shows that various EU countries assess very differently about the success of their energy efficient renovations (Url-1).

1.2.2 State of the art related to reference buildings

By considering existing buildings stock, it will be obvious that it is not rational to analysis cost for each building separately. From policy-making point of view, main cost analysis should be done for a large number of building to be efficient and to make large scale decisions. Initial investigation about building categorization that leads to define reference or benchmark buildings had been done in U.S. One of the first investigations about building categorisation is a research by Briggs et al. (1987). The categories developed in this study allow users to focus studies for gas-fired equipment on specific segments of the nation's office building sector. Categories were defined based on physical attributes such as size, age, and location and on building energy loads. The categories were designed to represent the entire office-building sector with a limited number of categories while reflecting as much of the diversity within the sector on energy as possible. Several previous projects focused on creating prototypical building models. Huang and his colleagues developed a series of prototypical buildings over several years (1991, 1995) and another paper presents an analysis of 1999 building data (1999). In 2005, the U.S. Department of Energy (DOE)

began creating a series of commercial building prototypes called Commercial Benchmarks that were intended for use in tracking the progress of all commercial programs included in DOE's Building Technologies program. Deru et al. (2006) have developed a set of 22 hypothetical benchmark buildings and weighting factors for nine locations across U.S. for 198 buildings. DOE has developed a set of standard Benchmark building descriptions for both new constructions and existing buildings (representing both pre-1980 and post-1980 building stock). The input parameters for the building models came from several sources. Some were determined from ASHRAE Standards 90.1-2004, 62.1-2004, and 62-1999 for new construction and Standard 90.1-1989 for post-1980 construction; others were determined from studies of data and standard practices. The development of these commercial Benchmarks was conducted by staff from three of DOE's national laboratories—Lawrence Berkeley National Laboratory (LBNL), National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL) (Dru et al., 2011). The Benchmarks were developed in DOE's EnergyPlus simulation tool and accompanied by documentation of each Benchmark building in the form of spreadsheet "scorecards" that provide descriptions, parameter values, and source data for all parts of the simulation model. A companion paper presents a methodology for selecting envelope and HVAC systems from data on the existing building stock (Winiarski et al., 2008). Also, a residential building benchmark from the DOE Building America program in 2005 that updated in 2009 is another benchmark or reference building in U.S. (NREL, 2009). Methods of energy saving in benchmark buildings located in 37 different locations in U.S. and the cost analyzes related to retrofit of them are included in recent research by National Renewable Energy Laboratory (Casey & Booten, 2011). Furthermore, lots of research has done about energy and cost analysis of Reference Buildings in U.S. (Kneifel, 2010; Stoki et al., 2007).

In the EU, the main regulatory framework is the Energy Performance of Buildings Directive (EPBD). The first version of EPBD (EU Parliament, 2002) that released in 2003, obligate Member States (M.S.) to guarantee that, during building construction, dealing or renting, an energy performance certificate is accessible to the owner or by the proprietor to the prospective purchaser or tenant, as the case might be. Also, it requires M.S. to categorize and classify buildings. To have a practical impact on EER of buildings, the recast version of EPBD (EU Parliament, 2010) obliges M.S. to define

minimum requirements for the energy performance of buildings and buildings components intending to achieving cost-optimal levels using a comparative methodology framework. It stated that the comparative methodology framework to determine the cost-optimum level of energy performance requirements for buildings and building elements should require M.S. to define reference buildings and energy efficiency measures to assess in reference buildings. Since it is not possible to calculate the cost-optimality for every single building, the comparative framework illustrated in the accompanying guidelines. Supplementing document of the EPBD requires M.S. to define a set of reference buildings (RBs), as typical national or regional buildings. (EU Comission, 2012). Due to the EPBD request, RBs have hence become a crucial topic for studies assessing the energy performance. In particular, two recent projects within the ‘‘Intelligent Energy Europe’’ program, TABULA (Loga & Diefenbach, 2010) and ASIEPI (Spiekman, 2010) hold a reference position concerning the definition of reference residential buildings across EU.

1.2.3 State of the art related to energy efficient retrofit's barriers

One of the main obstructions to energy efficient retrofit (EER) is fewer amounts of financial resources (Energy Efficiency Financial Institutions Group, 2015; The Building Performance Institute Europe, 2010). Especially in residential sector building owners hesitate to involve in related actions (T'Serclaes, 2007; Fuller, 2008). Scientists and decision makers in the construction sector are trying to develop high-applicable and cost-effective methods with low initial investment cost that can satisfy owners to involve in the actions as a self-financier.

The main challenge in every retrofit project is uncertainties, such as climate change, services change, human behavior change, government policy change, etc. which have a special influence on results and prosperity (Ma et al., 2012). Fewer amounts of financial resources and a high amount of initial investment cost are significant barriers to building stock's energy efficiency retrofit (Fuller, 2008). From building owners' and investors' point of view, low-cost levels of energy and environment-related improvements, as well as the poor economic profitability of energy efficiency measures, are reasons for the disappointment and lack of involvement in retrofit actions (Jakob, 2006). In line with increasing the awareness about benefits of energy efficiency for human life and future, by decreasing the initial investment cost it is possible to encourage building owners and even tenants to involve in the retrofit action

and to finance their owned buildings. When initial investment cost is high, the uncertainty and comeback period is high usually. Hence, buildings owners and tenants are not so excited and enthusiastic to involve in the retrofit actions. On the other hand, in rented buildings, since paying for the cost of the retrofit is the responsibility of building owners whereas the benefits often flow primarily to the tenants, building owners are unwilling to involve in retrofit programs (Ma et al., 2012). From governments' point of view, due to uncertainty in economic variables, financing such projects is irrational as well. One should keep in mind that even "a positive economic assessment of energy efficiency investments is not sufficient for the realization by investors, it is a necessary precondition" (Amstalden et al., 2007). But it should be kept in mind that, apart from environmental benefits like GHG emission reduction, the money that has spent for energy consumption have high benefits for a country with less available energy resource and plant and exit from the country while the money that has spent for energy retrofits mostly stay within the country and paid for labor, material, etc.

1.2.4 State of the art related to benefits of energy efficient retrofit

EER can create an appropriate infrastructure for new jobs; hence, governments should think two times about pros and cons of investment in EER. A study illustrated that deep renovation program in Hungary could create up to 131,000 net new jobs by 2020. Also, it is highlighted that up to 38% of the employment gains are because of the indirect consequences on other sectors that supply the construction industry and the induced effects of the increased spending power of higher employment levels (Ürge-Vorsatz et al., 2010). Furthermore, EER is affecting not only on energy usage of the buildings but also on occupants' productivity and performance. Ashrafian and Moazzen have illustrated the relation between building energy consumption and occupants' health and satisfaction (Ashrafian & Moazzen, 2014).

From total 42% of final energy-related saving that EU planned to have in building, industry and transport up to 2050, 11% is belong to building envelope, 4% belong to heating and cooling, and 1% belong to lighting. Half of the savings in the household is related to the building shell refurbishment of existing buildings. It is stated by Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of Germany that building-related efficiency options (refurbishment, replaced energy systems, highly efficient new buildings) trigger 80 percent of the cumulative energy

cost reduction in EU. Figure 1.2 indicates the potential of energy saving in the household for 2050 (Bobmann et al., 2012).

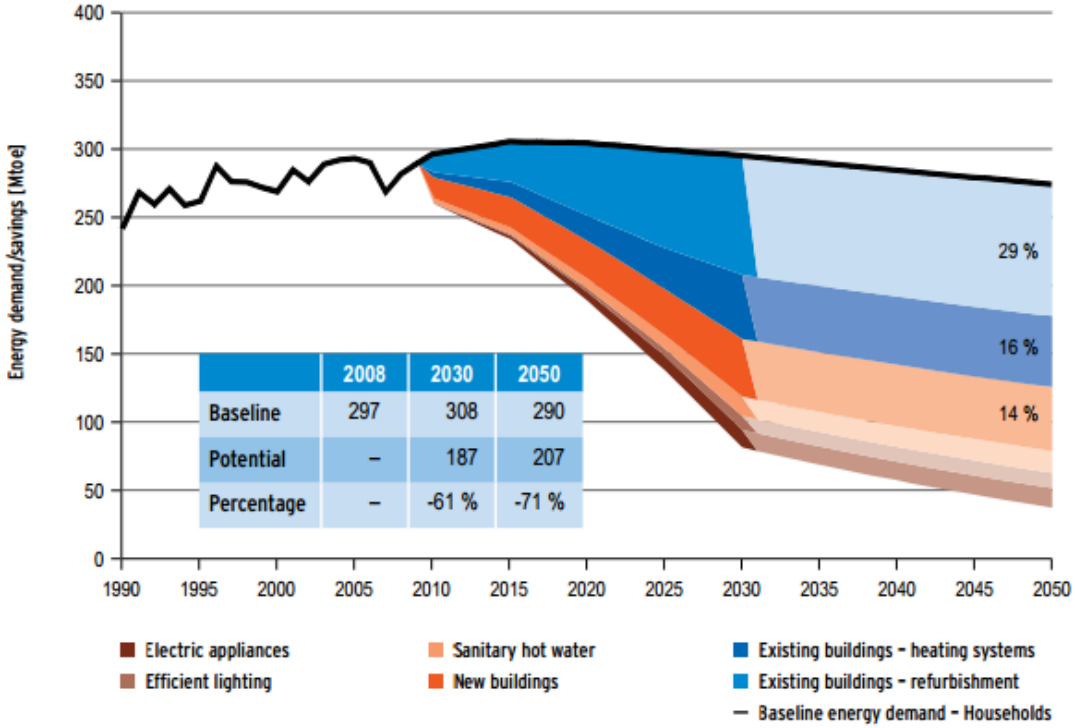

Figure 1.2: Energy Saving Potential in the household (Bobmann T. and others, 2012).

1.2.5 State of the art related to the cost analysis of energy-efficient retrofit

The Buildings Performance Institute Europe and European Council for an Energy Efficient Economy presented a calculation methodology for a cost-optimal level within the framework of the EPBD in 2010 and 2011 (Hermelink et al., 2013 & BPIE, 2010). Although there are many investigations in the field of retrofit cost and cost-effectiveness (Chidiaca et al., 2011; Mahlia et al., 2005; 2011), there are few studies in the area of cost-optimal retrofit of reference building as it is an entirely new area while it can be used more efficient in the macro economy. One of a few studies in this field is a paper by Fabrizio et al (2011) defined a reference model for a large office building, based on various studies over Italian office building stock. Corgnati et al. (2013) introduce the concept of reference buildings and the state of the art at an international level. In particular, authors illustrated a general methodology for the creation of reference buildings; also, Italian reference for an office building that introduced in previously mentioned research is analyzed in this research. Becchio et al. (2013) have done the cost-optimal analysis for related Italian reference building.

Aiming for future evaluation of the cost and energy effects of the new Egyptian energy standard a study by Attia, established two detailed benchmark residential building models describing the energy usage profiles for air conditioners, lighting, domestic hot water and appliances concerning buildings layout and construction (Attia et al., 2012). The International Energy Agency's (IEA), Energy in Buildings and Communities (EBC) Programme, carries out some researches and development activities in the field of cost analysis and efficiency measures during the EER of buildings. "Annex 56, Cost-Effective Energy & CO_2 Emissions Optimization in Building Renovation," is one of those activities. It is objected in Annex 56 to define a methodology for establishing cost-optimized targets for energy consumption and CO_2 emissions in building's renovation and to determine cost-effective combinations of energy efficiency and renewable energy supply measures (Url-2). Another on-going project is Annex 55, Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO). It is objected in Annex 55 to develop and validate probabilistic tools for energy use and life cycle cost (Url-3). From completed projects, Annex 50, Prefabricated Systems for Low Energy Renovation of Residential Buildings, pay attention to methods of using prefabrication for renovating the existing building that make the projects fast and cost-effective (Url-4; Schwehr et al., 2011). A report by ecofys, Polytecnico di Milano and University of Wuppertal, indicates the link and gap between the nearly zero-energy buildings and cost-optimal levels (Hermelink, 2013).

Directive 2012/27/EU (EU Parliament, 2012), Energy Efficiency Directive of EU (EED), requires renovation of the existing building stock with cost-effective approaches. Besides, it requires the M.S. to establish, by April 2014, a long-term strategy for mobilizing investment in the renovation of the national building stock, this strategy should encompass with the description of cost-effective approaches to improvements relevant to the construction type and climatic zone. That strategy should "address cost-effective deep improvements which lead to a refurbishment reduces both the delivered and the final energy consumption of a building by a significant percentage compared with the pre-renovation levels, leading to a very high energy performance". Also "obstacles to the renovating of the existing building stock based on a split of incentives between the different actors concerned should also be tackled at national level". This strategy must contain "staged" deep renovations as well. Not

only low initial investment cost but also staged retrofit with even medium and high investment cost can raise the number of retrofit projects in societies. What important about staged renovation is that distribution of retrofit actions to different period should decide accurately. The staged application can satisfy owners to involve in a retrofit project. A report by European Commission (2013) indicates how financial support for energy efficiency in buildings can improve.

One of low-cost energy efficient retrofit measure is occupant behavior change which has no or very low cost in comparison with interference in the current condition of a building. A survey by Owens J., and Wilhite H., (1988) showed that 10–20% of domestic energy use in the Nordic counties can be saved from occupant behaviour changes alone, while a study by Alajmi A. (2012) showed that non-retrofitting measures with no or low investment only saved 6.5% of building annual energy consumption, while the real retrofitting measures with significant investment can save up to 49.3% of annual energy consumption. Guerra Santin et al. (2009) studied the importance of household characteristics and occupant behavior on energy use for space and water heating in the Netherlands. The results showed that occupant characteristics and behavior significantly affect building energy use. The impact on energy use for heating is around 4.2%, for example. These studies showed that the changes in occupant behavior, occupant controls, and comfort range can lead to significant energy savings. Occupant behavior can change by attending to related courses or by a variety of educational and behavior change activities such as a public advertisement.

A decision on replacement or repairing the energy system is a critical option that has a special influence on the investment cost of the action. The costs of repairs should be weighed against the cost of a new system, taking into consideration the age and condition of the system. According to Krigger and Dorsi's (2009) research, if the cost of repairs is more than half the cost of replacement, it is better to replace with a new system than to invest in repairing an old one. Figure 1.3 is extracted from similar researches in this field to determine whether a system should be replaced or repaired.

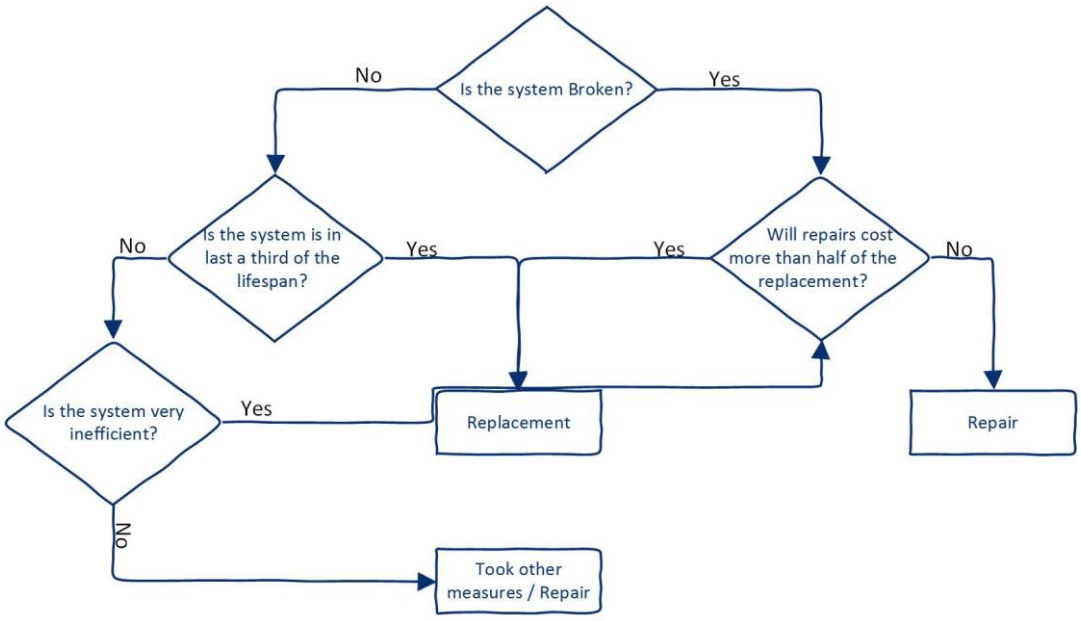

Figure 1.3: Decision making the process for replacement or repair in retrofit action.

1.2.6 State of the art related to buildings' energy efficient retrofit in turkey

In line with EU, there are ongoing and concluded studies on energy efficiency retrofit in Turkey. The Energy Efficiency Law is established in 2007 (Turkish Offical Gazette, 2007). Through Bep-TR project, the base for building certification process is provided and a national energy performance calculation method is developed (Turkish Official Gazette, 2008 & 2010). Reference buildings for cost-optimality analysis are developed through a project supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK). Cost-optimality analyzes are done for some of those reference buildings in that study (Yilmaz et al., 2015).

Moreover, in Turkey, buildings are account for about 35% of whole energy consumption (Keskin, 2010) and have 30% energy saving potential; this lead to approximately 2250 million dollars saving for country. (Ipek et al., 2012) In 1985, a regulation about heat insulation in buildings was established by The Ministry of Public Works and Settlement (Official Gazete, 1985). Heat insulation standard of Turkey (TS-825) became a mandatory for every building in 2000. However, there were some regulations about energy systems in buildings; there wasn't any mandatory obligation about heat insulation or other energy efficiency measures in the country before 2000. (Apak & Ubay, 2007) Buildings, which are made before 2000, have at least two times more energy consumption than buildings that are made based on current legislations. (Keskin, 2010) According to Turkish Statistical Institute statistics (TÜİK), from about

9 million existing buildings whole around the country in 2013 at least 75%, that is equal to 6.75 million, are built before 2000. At the 3% yearly renovation rate and $10000 initial investment cost, the required yearly budget is 2026 million dollars.

1.3 Hypothesis

In the era of technology, renewable energy, and development, consuming huge amount of energy by buildings is a disadvantage for every country. Rather than burn the money to provide comfort level indoor and to import energy from other countries it is recommended to provide building sector with energy efficiency aspects. In this thesis, it is hypothesized that by applying different energy efficient retrofit measures to the existing buildings it is possible to save energy in huge amount and reduce the global cost in a considerable amount while keep the investment cost in the reasonable amount. Besides, it is hypothesized that the amount of benefits araised from step-by-step application of the energy efficient retrofits is much more than loses. By using step-by-step retrofit it is possible to reach to a high amount of energy and cost saving for Turkey. To verify the hypothesis, assessment about the feasibility of renovation packages, the ideal process of renovation applications, cost and energy performance analysis, determination of the feasibility and practicability in the national market included during the whole process of the thesis.

2. PROGRESS IN THE FIELD OF REFERENCE BUILDINGS, NEARLY ZERO ENERGY BUILDINGS AND COST-OPTIMAL BUILDINGS' RETROFIT

2.1 Purpose

Without a concrete infrastructure and proper investigation, it is impossible to conduct a useful research. The purpose of this chapter is to provide a base for the rest of the thesis. The definitions and progress in the idea of the thesis are confined in this chapter. Reference buildings, nearly zero energy buildings, and cost-optimal energy efficient buildings' retrofit together with a global cost that are main issues in the thesis are going to be focused in this section. Indeed, the main issues related to the thesis are explained here.

2.2 Reference Building's Definition

By considering the number of buildings in existing buildings stock, it will be obvious that it is not rational to analysis energy and cost for each building separately. Most of the buildings that are constructed in the same time-period have same characteristics that mostly effects on the energy performance of buildings. From these characteristics, just buildings' form and direction can vary among such buildings. Also, from policy making point of view, it is proper that cost and energy analyzes were done for some buildings that can be representative for a large number of buildings to make large scale decisions. Thus, it is necessary to define buildings that can represent a large number of buildings to carry out energy and cost analysis. These buildings are called as Reference Buildings (R.Bs).

Annex III of the EPBD-Recast defines R.Bs as "buildings characterized by and representative of their functionality and geographic location, including indoor and outdoor climate conditions." They "shall cover residential and non-residential buildings, both new and existing ones".

According to Corgnati et al. (2013), there are three methods to define R.Bs. The methods are as following:

- Selection of "Real" R.Bs: in this method the real existing buildings, with average characteristics based on statistical analysis is chosen to be R.Bs. Hence, it is necessary to have a reliable and large amount of information on the building stock.
- Creation of "Theoretical" R.Bs: this method processes statistical data to define RBs as a statistical composite of the features found within a category of buildings in the stock. Thus, the buildings are made of the most commonly used materials and energy related systems.
- Creation of "Example" R.Bs: the method is used when there isn't any available statistical data, and thus experts' assumption and studies provide a base for determination. Real or theoretical buildings will be considered to represent the R.Bs.

The choice between these three options depends on different circumstances, data availability, etc. Different types of approach should be used to describe different building categories. The essential information for determination of R.Bs are size and geometry, building envelope information (such as glazing ratio, transmittance values, insulation thickness, material performances, technical systems), operation information (such as user profile, occupancy rate, and related schedules) and energy systems' information (such as lighting and HVAC systems and fuel type).

2.3 Cost-optimal Level's Definition

As stated by EPBD-Recast, "cost-optimal level' means the energy performance level which leads to the lowest cost during the estimated economic lifecycle, where:

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

- the estimated economic lifecycle is determined by each Member State. It refers to the remaining estimated economic lifecycle of a building where energy performance

requirements are set for the building as a whole, or to the estimated economic lifecycle of a building element where energy performance requirements are set for building elements."

Cost-optimal levels have to be derived by comparing the global cost calculation results of different measures/packages/variants. EPBD-Recast persists that MSs should drive a national methodology to define cost-optimal requirements. The methodology requires MSs to:

- Establish R.Bs that are representative regarding building function and climatic conditions. The R.Bs need to cover residential and non-residential buildings, both for new and existing,
- determine energy efficiency measures/packages/variants to be assessed for the R.Bs. These can be measures for buildings as a whole, for building elements, or for a combination of building elements,
- calculate the final and primary energy consumptions of these R.Bs before and after application of energy efficiency measures,
- calculate the global costs of the energy efficiency measures during the required calculation period of the R.Bs, that is 30 years for residential and public buildings, and 20 years for commercial, non-residential buildings. Investment costs, maintenance and operating costs, earnings from energy produced (if applicable) and disposal costs (if applicable) need to be taken into consideration for the calculation period. To calculate the results at the macroeconomic level, the cost of greenhouse gas emissions should be taken into account.

From the variety of specific results for the assessed measures, a specific cost curve can be developed (Figure 2.1). The combination of measures with the lowest cost will provide the minimum level of the requirement at the optimal cost. If packages should have the same cost, the package with the lower energy use should normally be selected. In reality, the targeted large number of solutions will most probably not form an exact curve. It can be assumed that the data sets will form a "cloud" from which an average curve can be derived (Boermans et al., 2011).

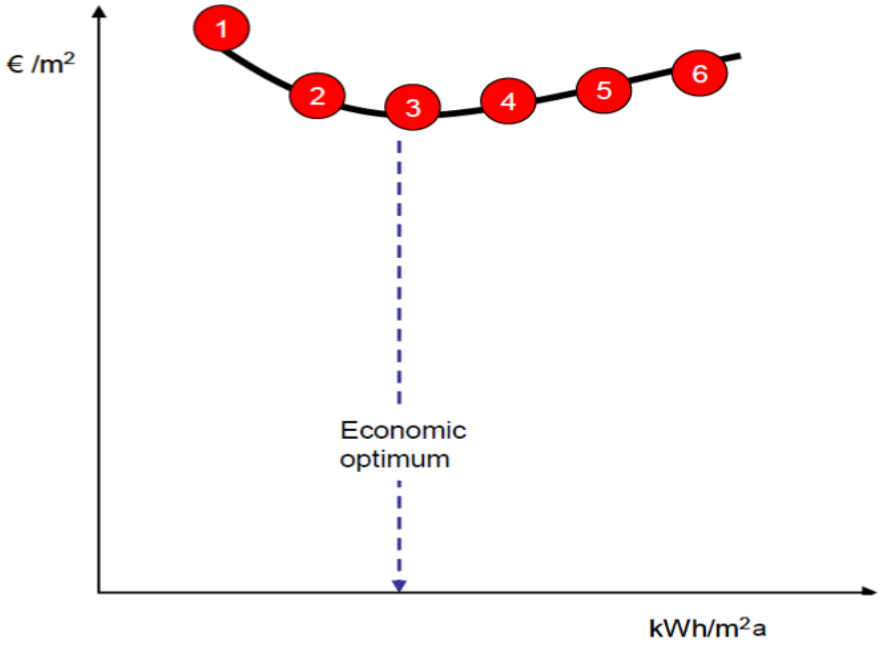

Figure 2.1 : A sample of cost-optimality graph (Boermans et al., 2011).

2.4 Nearly Zero Energy Building's (nZEB) Definition

EPBD-Recast determined, for the first time at the legislative level, the concept of nearly zero energy buildings as a building that is very high energy performance building requiring almost zero or a very low amount of energy. It will be largely covered by energy from renewable sources including renewable energy produced on-site or nearby. Indeed, nZEBs are buildings with a quasi-zero energy demand and very high energy performance. It is stated by EPBD-Recast that as of 2019, public authorities' new buildings should be the "nearly zero-energy buildings" and from 2021, all new buildings must be the nZEBs. Also, M.Ss should develop policies and set concrete targets to increase the number of nZEBs resulting from building refurbishment. Thus, it is necessary to guarantee that energy performance of buildings, intended to retrofit, is improved to meet the minimum energy performance requirements. These requirements shall be applied to the building that has to be retrofitted or to individual building elements restructured.

Figure 2.2 is showing the cost-optimal and nZEB buildings location and gaps between these two issues in the cost-optimality graph.

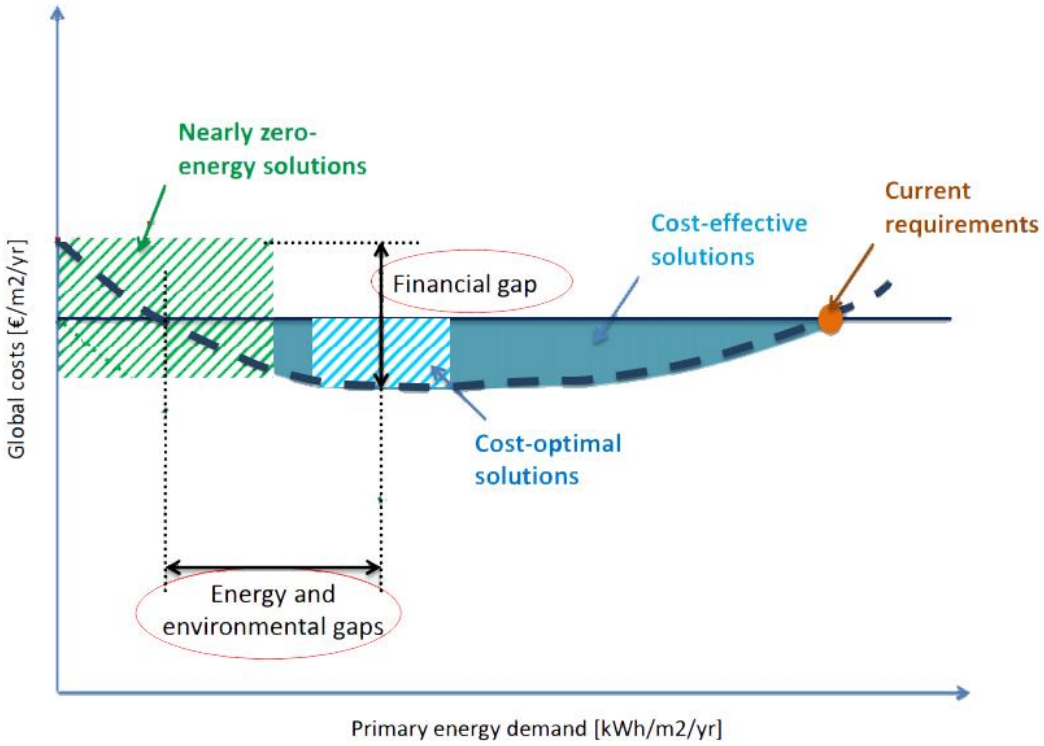

Figure 2.2 : Differences between Cost-optimal and nZEB buildings.

2.5 Global Cost's Definition

The term 'global costs' is taken from standard EN 15459 and corresponds to what generally in the literature is called "lifecycle cost analysis." According to EN 15459-2007, the global cost is "sum of the present value of all costs (referred to the starting year) including investment costs. At the end of the calculation period, the deconstruction costs or the residual value of the components should be taken into account to determine final costs". The cost of land is excluded from the calculation. The calculation of global cost considers the initial investment cost, the sum of annual costs of maintenance, energy and running for every year, replacement costs and the residual value as well as disposal costs if appropriate, all concerning the starting year. Global cost calculations engender from "net present value" of costs incurred during a defined calculation period, taking into account the residual values of equipment with longer lifetimes.

The privilege of the global cost method is that, opposed to the annuity method, it allows the use of a calculation period (reinforced with a residual value of long-lasting equipment) and that "it can make use of lifecycle costing (LCC) which is also based on net present value calculations. The global cost concept is not fully in line with a

complete life cycle assessment (LCA) that would take into account all environmental impacts throughout the lifecycle" (EU Commission, 2012).

2.6 EU's Progress in the Field of Reference Building, Nearly Zero Energy Buildings and Cost Optimal Buildings' Retrofit

Low energy consumption buildings developments are always supporting by the European Union. I this way, lots of directives have been taken into account; in 1993 European Council published Directive 93/76/EEC, to curb carbon dioxide emissions and improve the energy efficiency. Thereupon, there was the Directive 2002/91/EC of the European Parliament, Energy Performance of Buildings Directive (EPBD), enacted on December 16, 2002, and come into force in 2003; it deals with the energy performance of buildings. This Directive was aimed to promote the energy improvements of buildings within the Community, while outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness, are taken into account.

This directive was enacted after the Kyoto Protocol, an international agreement signed by United Nations Framework Convention on Climate Change (UNFCCC) in 1997, and entered into force eight years later in 2005; the main objective of this agreement was to decrease the greenhouse gas emissions whole around the world. Since the importance of the energy performance of buildings' improvement was cleared for all EU Member States, it was considered necessary to introduce a directive, EPBD, defining in a better way the minimum requirements for the energy performance of buildings.

As an implementation of the first EPBD Directive 2002/91/EC, the Directive 2010/31/EU, EPBD-Recast, was established. It was consisted of 31 articles; the aim of this revision was the same of the previous directive, while clarify and simplify certain provisions, extend the scopes, strength the effectiveness and make additions such as:

- Adoption of an energy performance of buildings calculation methodology common to all Member States;
- The calculation of cost-optimal levels for energy performance minimum requirements;
- The realization of Nearly Zero Energy Buildings.

EPBD-Recast requires the Member States to define different characteristics to achieve cost-optimal levels both for new and existing buildings. It supported some new targets that mostly defined by the European Council of March 2007, to be achieved by 2020, as reducing by 20% the energy consumption, increasing by 20% the energy production from renewable sources and improving by 20% the energy efficiency across EU.

Since it is impossible to identify the cost-optimality for every single existing building, EPBD-Recast introduces the concept of R.Bs, as typical national or regional buildings; then, Member States are required to setup these R.Bs to make the calculations at the national level.

In 2013, the average annual specific consumption per square meter for all types of building across EU was around 215 kWh/m^2. Non-residential buildings were on average 70% more energy consumer than residential buildings, with a consumption of 311 kWh/m^2 compared to 184 kWh/m^2. While the total area of residential buildings causes to the fact that the total energy consumption in the residential sector is twice as much as a non-residential sector.

According to the EPBD-Recast, by 2020, all new buildings in the EU should be "nearly-zero energy buildings" (nZEB). The required decrease in energy consumption of "low energy buildings" will range from 30% to 50% of current requirements for new buildings under existing regulations. (European Environment Agency, 2016) Figure 2.3 illustrates the primary energy consumption per m^2 for nZEB (new buildings) in some EU M.Ss. There is no single, harmonized definition of nZEB across EU. Different nZEB approaches and criteria are used in EU countries, which doesn't allow for a fair comparison. For most of the countries, new nZEB buildings are expected to have less than 50 $kWhm^2/yr$ energy consumption (including energy use for water heating, AC, ventilation and lighting). For some other countries, i.e. Latvia, Cyprus, Romania and Austria primary energy consumption is higher (Figure 2.3).

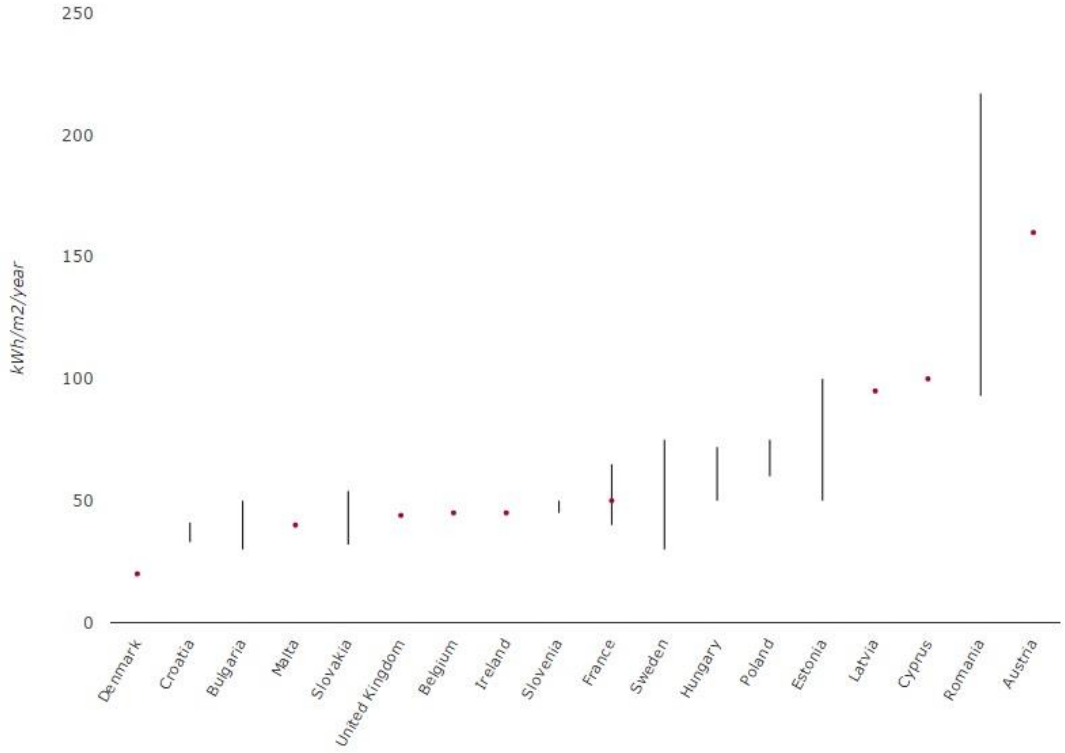

Figure 2.3 : NZEB requirements for new buildings in some EU countries (European Environment Agency, 2016).

2.6.1 Directive 2002/91/EC: The Energy Performance of Buildings (EPBD)

The Directive on the Energy Performance of Buildings was the first main agreement at a European scale to fix goals on energy use within buildings. The general aim is to reduce the energy consumption in the built environment by 20% by 2020, compared to the 1990 level. The main actions taken on the existing building stock were:

- To create a methodology that calculates the integrated energy performance of buildings;

- To establish minimum standards when an existing building is subject to a major renovation;

- To create certificates assessing the performance of building: Energy Performance Certificate;

- To establish a regular control and inspection in HVAC (Heating, Ventilation, and Air Conditioning) systems.

The Energy Performance of Buildings Directive (2002/91/EC) was the main legal instrument of the EU for energy efficiency in buildings since 2003 to 2010. It aims to

generate a common sensibility aiming at improving the energy performance of buildings among the EU countries. The directive proposed an adaptation period, which ended in January 2006, for each country to prepare its legislation concerning the energy performance of buildings.

2.6.2 Directive 2010/31/EU: The Energy Performance of Buildings – Recast (EPBD-Recast)

Directive 2010/31/EU recasting the Directive 2002/91/EC on energy performance of buildings (EPBD) promotes the improvement of the energy performance of buildings within the European Union, taking into account all types of energy uses (heating, lighting, cooling, air conditioning, ventilation) and outdoor climatic and local market conditions, as well as indoor climate requirements and cost-effectiveness.

The Comparative Methodology Framework indicated in Annex III of EPBD-Recast, is accompanied by Commission Delegated Regulation to compel the MSs to: Establish at least nine R.Bs for Single-family, multifamily, and office buildings respectively, one for new buildings and two for existing buildings subject to major renovation. In addition to office buildings, MSs should establish R.Bs for other non-residential building types where energy performance requirements exist.

It is obligated by the EPBD-Recast that all existing buildings undergo renovation to meet minimum energy performance requirements to (or "intending to") achieving the cost-optimal level. These minimum requirements should be set for building elements. Also, it is stated that policy should be developed, and measures should be taken to stimulate and transform existing buildings into nearly zero energy buildings while nZEBs should be defined according to national, regional or local conditions. Each Member States (MS) should plan to promote nZEBs measures for existing buildings. Policymaking regarding all of these obligations requires having a wide overview of the market. It is estimated that financial option regarding nZEBs requirements retrofits is rare due to lack of awareness among governments and policy makers.

The EPBD-recast obligated countries to provide a national methodology that defined the cost-optimal level of buildings retrofit while the related EU directive provides a calculation methodology. This calculation methodology acts as a framework and describes a general approach by which national methods can be implemented. All of

the steps involved in the cost-optimal calculation method are interrelated and need to be investigated at the national level in detail. Throughout the adaptation of the general framework methodology, it is important that the method is strengthened by taking domestic market conditions into consideration.

2.6.3 Directive 2012/27/EU: Energy Efficiency

Energy Efficiency Directive (EED) 2012 obligates MS to renovate central governmental buildings by 3% of the total floor area yearly after 1st January 2014. It is required to establish a long-term strategy for mobilizing investment in deep cost-effective renovations of buildings stock, including staged deep renovations. Also, measures for a behavioral change of occupants is encouraged to be determined by MSs.

2.7 Turkey's progress in the field of reference building, nearly zero energy buildings and cost optimal buildings' retrofit

TS 825 Turkish Standard (Thermal Insulation Requirements for Buildings) has the reference rule in Turkey and its last review was published in 2013. It is a mandatory standard which aims to increase energy saving and define a methodology to determine energy demand. Moreover, only heating energy demand is included in this standard while there isn't any information related to other energy systems.

Within the harmonization procedure of EU legislations, Turkey has been keeping up with related EU legislation after 2007 (Turkish Official Gazette, 2007 & 2008 & 2010). An Energy Efficiency Law and Building Energy Performance Regulation in accordance with EU legislations were enacted. The Energy Efficiency Law was published in 2007 and the aimed to boost energy efficiency to reduce the financial burden and environmental impact. After this law, a regulation on building energy performance (Bep-tr) came to the force and included requirements for design parameters, heating and cooling energy demand, heat insulation, hot water and lighting in buildings for energy certification.

Building Energy Performance Regulation entered into force in December 2008 by Ministry of Public Works and Settlement and was revised in 2010 (Turkish Official Gazette, 2008 & 2010). The purposes of this regulation were to define the energy calculation procedures, energy certification procedures and minimum energy

performance requirements for new and existing buildings. It also aims to increase the efficiency of building energy systems and efficient use of energy resources in buildings, prevent from energy waste and to regulate the principles of environmental protection.

In line with European countries, R.Bs for cost-optimal analysis are established through a TUBITAK supported project. Based on building market's real conditions, 26 different R.Bs for residential buildings were defined in three main categories: Sigle Family Houses, Apartment Buildings, and High-Rise Luxury Buildings. The buildings that were defined using the virtual method have been distributed in three periods: 1985-1999, 2000-2008 and 2009-2013. Some buildings have same geometry but different construction period that causes to different envelope and energy system characteristics (Yilmaz et al., 2015).

2.7.1 Law 5627: The Energy Efficiency Law

"The Energy Efficiency Law" in Turkey with the Law No. 5627 was published on 2007. The Law aims at increasing the energy related efficiency to provide efficient energy consumption, prevent excess energy, moderate the economical load due to energy costs and preserve the environment. For the promotion of energy efficiency, the Law indicates the importance of training and awareness raising activities. Regarding energy efficiency improvement, the Law determines the appointment of energy managers for some specific buildings' typologies. The regulation, which determines building's energy performance strategies, is to be applied in residential buildings with the indicated construction surface areas by the regulation, commercial and service buildings. This Law applies an amendment in the Condominium Ownership Law no.634. The changes in heating insulation, fuel type of the heating system and transformations between individual and central heating systems are applied by the majority of the number and land share of the condominium owners. However, a unanimous vote by the number and land share of the condominium owners shall be required to convert the central heating system to an individual heating system for buildings with a total construction surface area of two thousand square meters or above.

2.7.2 Regulation on the Building Energy Performance of Turkey (BEP-Tr)

In accordance with the Energy Efficiency Law in Turkey, the Building Energy Performance (BEP-Tr) Regulation has been introduced in 2008 and modified in 2010. The BEP regulation aims at ensuring energy efficiency in buildings and protecting the environment. In this context, the regulation obliges to keep heating, cooling, ventilation and lighting energy demand and consumption at a minimum level and also to take advantage of natural energy sources. Regarding these objectives, the regulation introduces some obligations related to building layout, envelope properties, Lighting and HVAC systems design and renewable energy use. Although these obligations are not difficult to achieve, the market resists implementation of the regulation in practice. Therefore, solutions for the market barriers that prevent implementation should be developed in detail also in line with the BEP Regulation. During these examinations national energy performance calculation methodology named BEP-Tr, which was developed in accordance with BEP regulation, should be considered as well. The main problematic points of the implementation of this method are related to market's perspective and national standards.

2.7.3 Determination of turkish reference buildings and national method for defining cost optimum energy efficiency level of buildings (TUBITAK - 113m596)

Throughout this research project supported by The Scientific and Technological Research Council of Turkey (TUBITAK), a legislation compatible national framework was developed for cost-optimal energy efficiency level calculations. In this regard, the R.Bs and the definition method were established for Turkey in accordance with EPBD-Recast. The reference building definition method was applied to residential building typologies which have priority and thus the main method was developed which can be developed through other building's types.

There are some yearly statistical data for building sector related to the existing buildings provided by Turkish Statistical Institute (TÜİK). These data are the number of floor, area, the construction materials, the structural system, the heating systems and their fuel types and the domestic hot water system (DHW) and their fuel type. So, it is possible to define the most representative characteristics for the reference buildings.

For example, it is clear that five story buildings are more prevelant among residential apartment buildings or the brick is the most representative material for exterior wall system of the residential buildings. Based on the TÜİK statistics and real market analysis, general buildings characteristics such as floor area and number, shape, envelope materials, transparency ratio, mechanical systems and user profile were determined, and R.Bs' geometry was established. In case of deficiencies in the realted data, some assumptions were taken to the account then meeting and workshops with experts were conducted to verify necessary assumptions. There is not any available statistical information about the heat transfer coefficients of envelope materials, thus it is assumed that buildings are providing the maximum limit values allowed in the national heat insulation standard, TS825. The Bep-Tr provided a base for some assumption like infiltration rate. The Reference Buildings are categories based on typology and construction period. Single Family Houses, Standard Apartment Buildings, and High-Rise Residential Buildings are distributed in three construction periods: 1985-1999, 2000-2008 and 2009-2013. Construction periods were distinct based on national regulations' and standards' implementation year. As stated in section 1.2.5, in 1985, a regulation about heat insulation in buildings was established by The Ministry of Public Works and Settlement and in 2000, heat insulation standard of Turkey (TS-825) was established. This standard was revised in 2008 and 2013.

User profiles and usage hours for residential buildings were defined in this study for Turkish residential buildings. According to 2011 Population and Housing Census, average household size is 3.6 in Istanbul. 54% of the household in Turkey consist of a couple with children. Hence, it is assumed that each R.Bs hosts a family consists of parents and two children. Energy systems for each construction periods were determined as well and verified through a workshop with experts. Also, a database was established for R.Bs. Energy performance level and minimum energy performance requirements were determined. Related cost-optimality analysis was done for a variety of energy efficient retrofit measures for some R.Bs.

A total number of 26 R.Bs are determined through related research study in three buildings' typologies and in three construction periods. Some buildings have same shape and geometry but different construction period and thus different envelope and energy systems (Figure 2.4, Figure 2.5 and Figure 2.6).

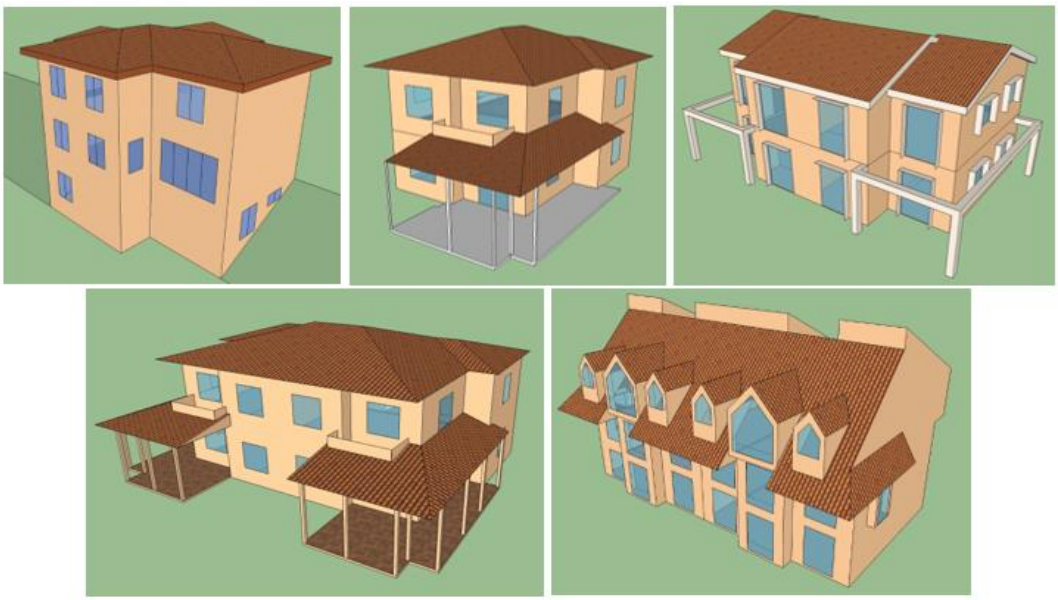

Figure 2.4 : The geometry of Reference Building for Single Family Houses (Yilmaz et al., 2015).

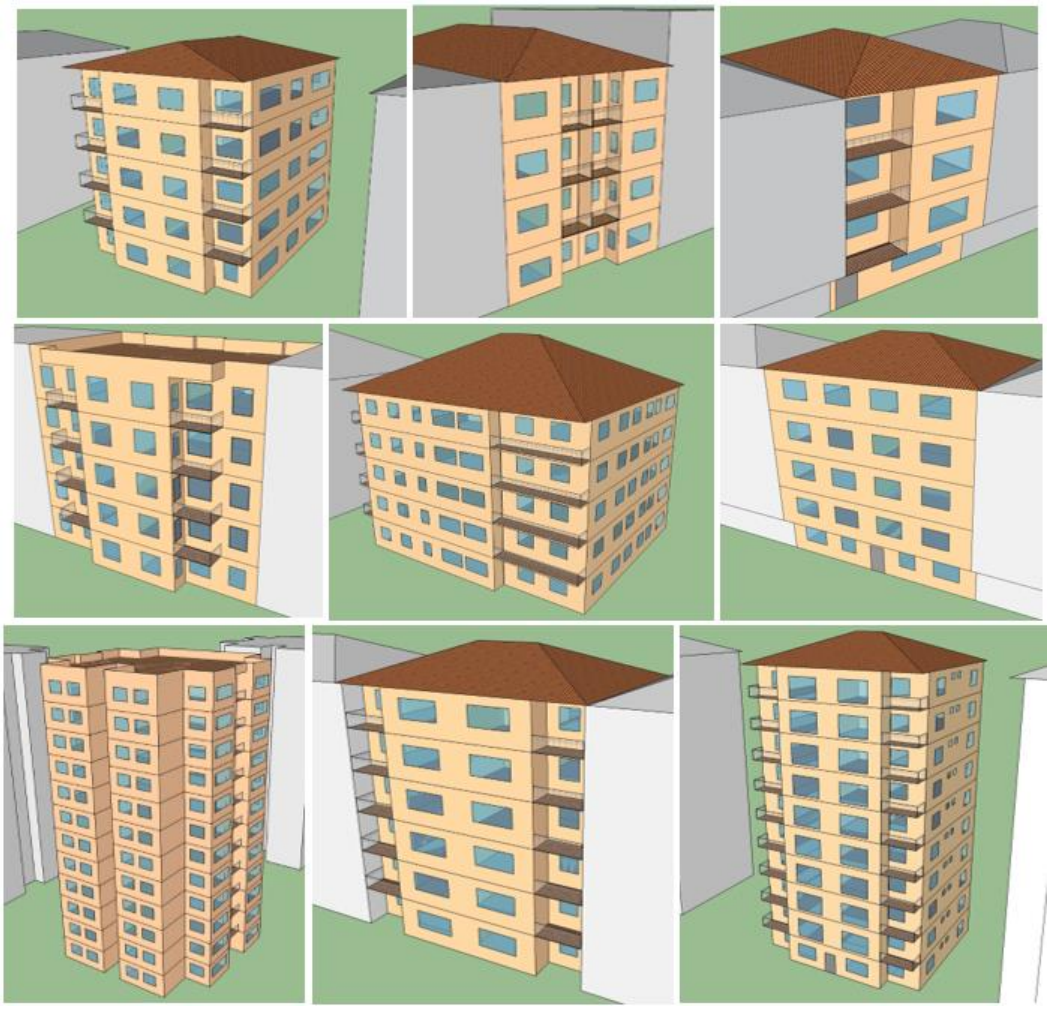

Figure 2.5 : The geometry of Reference Building for Standard Apartment Buildings (Yilmaz et al, 2015).

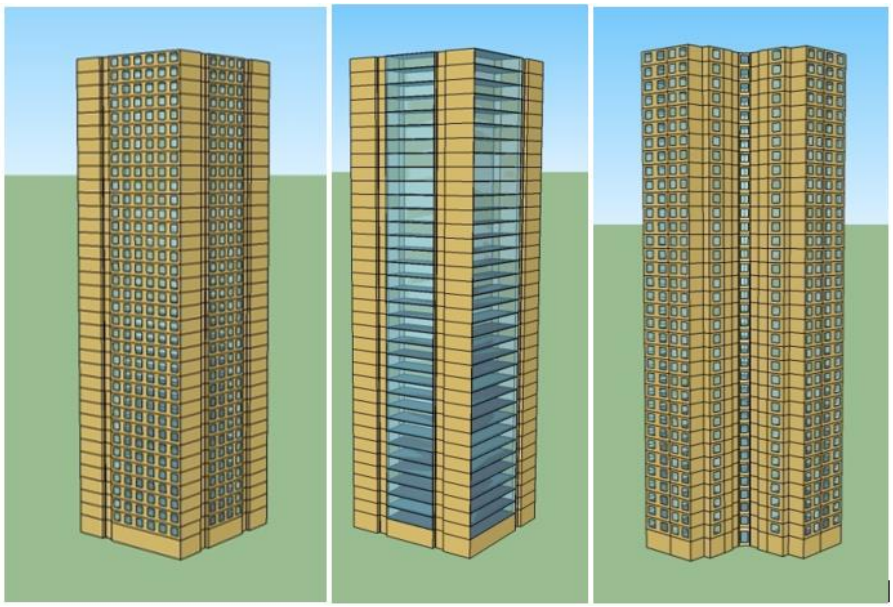

Figure 2.6 : The geometry of Reference Building for High-Rise Residential Buildings (Yilmaz et al, 2015).

3. METHODOLOGY TO DEFINE ECONOMICALLY APPLICABLE RETROFIT SOLUTIONS

Using an appropriate methodology for every research is necessary. If the inappropriate methodology is used, or if the appropriate methodology is used poorly, the results of the research could be misleading and even devastating. There are five most important aspects of the research methodology: design, sampling, calculation, data collection and data analysis. This thesis study is mostly based on calculation while some data gathering and analysis have been done during the research.

The main objective of this study is to provide a methodology to define economically applicable solutions for energy efficient retrofitting of existing residential building in Turkey. Thus, a specific method that is based on the methodology framework described in EU Commission Delegated Regulation (EU Parliament, 2012) is used. That framework is called "Cost-Optimal Methodology Framework" and has six main clauses:

- reference buildings establishment,
- identification of energy efficiency measures to assess on each reference building,
- calculation of the primary energy demands to result from the application of the energy efficiency measures on each of reference buildings,
- calculation of the global cost regarding net present value for each reference building,
- undertaking a sensitivity analysis for economic variations,
- derivation of a cost-optimal level of energy performance for each reference building.

The specific methodology for this thesis has seven main steps, starts from reference building determination. In general, the methodology of this study has following steps:

Step 1: Determination of the case study residential buildings and their physical, thermos-physical and active and passive energy systems together with operational profile,

Step 2: Determination of energy performance of the case study residential buildings by means of the primary energy consumption,

Step 3: Determination of retrofit measures and packages,

Step 4: Carry out of energy-cost analyses for the retrofit measures and determination of optimum measure/measures based on the amount of costs that will be saved and should be paid by owners. The energy analyses include primary energy consumption and CO_2 emission determination while economic analyses for the retrofit measures include initial investment cost and global cost determination for the calculation period. This step includes payback period determination and sensitivity analysis together with derivation of cost optimum level for retrofit measures,

Step 5: Determination of proper step-by-step retrofit scenarios and Carry out of energy-cost analyses for them, in case that the investment cost per each flat owner is more than the reasonable amount,

Step 6: Undertaken sensitivity analyses for the economic variations (Figure 3.1).

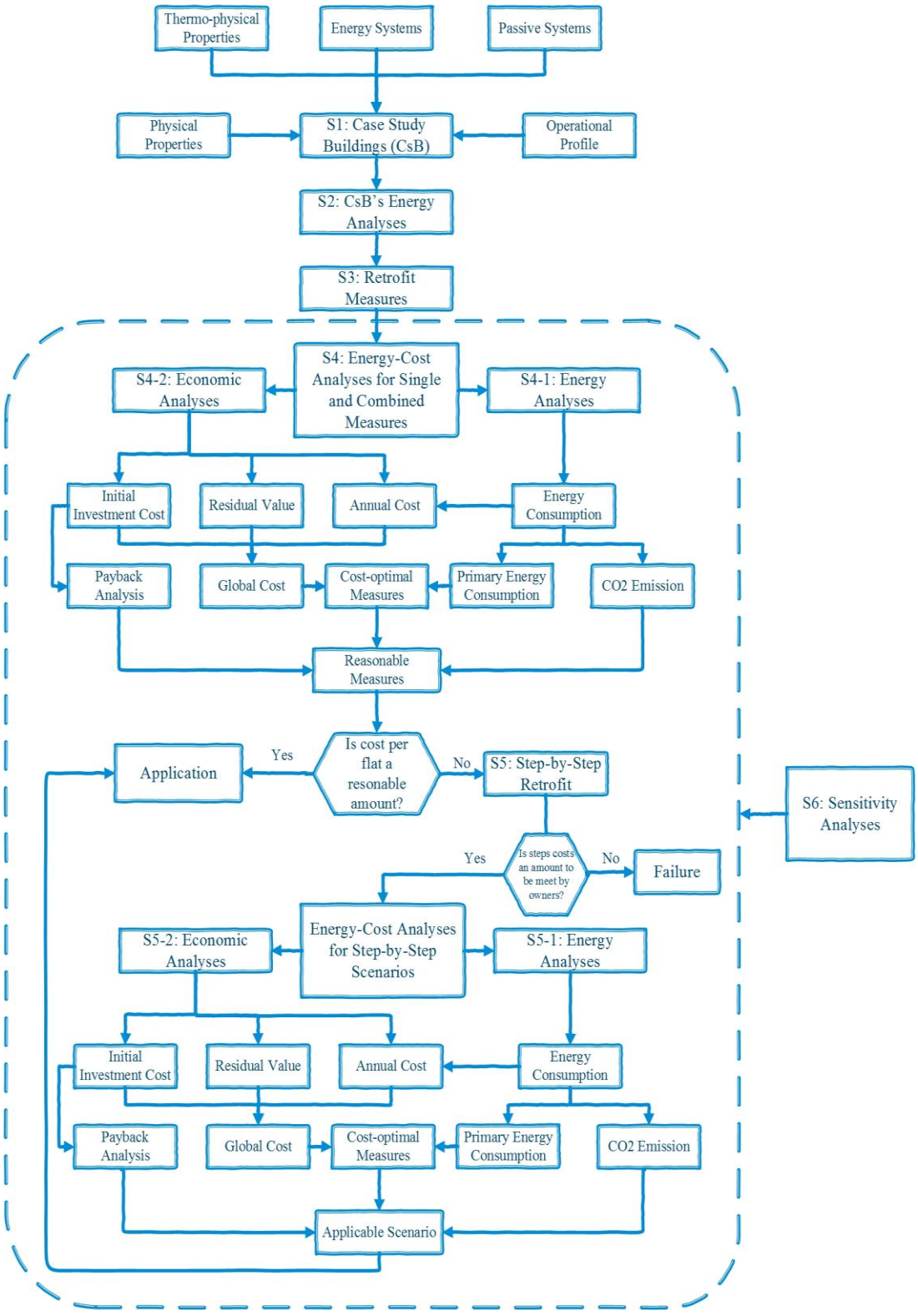

Figure 3.1 : The flowchart of the methodology to define economically applicable scenarios during energy efficient retrofit of existing buildings.

3.1 Determination of the Case Study Residential Buildings and their Physical, Thermo-physical, Active and Passive Energy Systems' Properties together with User Profile

According to EPBD-Recast, the reference building is "a hypothetical or real reference building that represents the typical building geometry and systems, typical energy performance for both building envelope and systems, typical functionality and typical cost structure" and "is representative of climatic conditions and geographic location". To decision making in a macro level, reference buildings are very useful. Any study related to reference buildings can be disseminated to a huge number of the buildings in a climatic region.

To define the reference buildings, detailed statistical and technical information are necessary. Precise data related to buildings' geometry, direction, envelope properties, the number of floors, transparency ratio, age and construction period, thermal zones, HVAC and lighting systems and their working schedules, occupants' number and their tendencies, auxiliary systems should be obtained to establish reference buildings.

Thermophysical properties that should be obtained for opaque and glazing systems are: opaque and glazing systems' U-value, Solar Heat Gain Coefficient (SHGC), visible transmittance ratio (T_{vis}), thickness of the materials (wall, ceiling and floor), infiltration rate, thermal mass of building elements (thermal capacity, specific heat and density), internal and external shading devices, position of windows in the wall, shgc of windows, orientation of openings, windows frame and dividers material and characteristics, shading elements properties.

For building systems the following should be defined: HVAC systems characteristics, lighting systems characteristics, schedules, set-point temperatures, ventilation rates, natural and/or artificial ventilation, humidity levels, and set-points, domestic hot water system, lighting level, equipment information and internal gains, type of fuel, renewable systems and control methods (manual or/and automatic).

User profiles should be analyzed from the number of occupants, schedules, equipment usage tendencies, clothing rate and activity level points of view. Some international standards will help to define occupants' related data. For instance: ASHRAE Fundamentals 2009, EN 14683 and DIN 18599 contains some useful information related to occupants.

The process of obtaining related data is playing a crucial role in the determination of the reference buildings. These date should be defined through a rigorous investigation. Some data are provided by national statistical institution, while some data are not available in any national statistics. Thses data should be obtained from experts' assumptions through various meeting and workshops. After obtaining required information, the reference buildings should be established. There are three methods to create reference buildings: Example, Real Existing, and Hypothetical methods.

- Example building method: When there is not any or a few reliable statistical information related to building stock, relying on experts' assumption is inevitable. Such an example building will represent the most probable of a group of buildings, within a selected location and age.
- Real building method: When reliable statistical data are indicating that a real existing building can represent a huge amount of the buildings in its category, that building can be selected as a reference building.
- Hypothetical building method: If there isn't any real building that can represent its category then a virtual building should be created. Such a building contains characteristics that are available for most of the buildings in a category.

All reference buildings that were established for Turkey are hypothetical buildings.

3.2 Determination of Energy Performance of the Case Study Residential Buildings

The aim of this section is to define the amount of energy consumption for the case study residential buildings. There are three methods to determine the energy performance (EP) of a building: measurement, manual and computational calculations. When a case study building is a real building, it is possible to use on-site measurement. Otherwise, manual or computational calculations should be performed to determine the EP of a building. There are some national and international standards and methods to calculate EP of a building. EN 15603, DIN 18599 and BEP-Tr are some of them.

On-site measurement and manual calculation are time-consuming methods. By considering the number of possible scenarios in the next steps, it is irrational to use such determination methods. If the EP of the case study buildings determined by one of those methods and further analysis were done by computational calculations, the

calibration of the results would be challenging and unreliable. Thus, it is preferred to use computational calculations method for EP determination of case study buildings and related measures.

"EnergyPlus" is a widely used simulation software under license from U.S. Department of Energy (DOE) to define EP of buildings. This detailed dynamic simulation tool can calculate the EP of building in different time periods. The one-year period is proper calculation period for this study. Weather data file that is critical to the accuracy of the simulation results should obtain from DOE website or generate from the average multi-year weather data. Another simulation tool that is very useful in EP calculation is "DesignBuilder". This software is using "EnergyPlus" as a calculation algorithm. The modeling in the EnergyPlus is complicated. On the other hand, simulation in the DesignBuilder is unreliable as some of important data are not in the limelight. Thus, a combination of these tools is more reliable than using just one of them. It is recommended to do modeling in the DesignBuilder and then export the model to EnergyPlus and continue to the simulation there.

To define the cost-optimal scenarios, primary energy consumption of the building should be defined. Primary energy is energy that has not been subjected to any conversion or transformation process. (EN 15603, 2008) Based on the primary energy consumption and global costs associated with the different retrofit scenarios assessed for the defined reference building, the global cost vs. primary energy consumption graphs would be drawn and cost-optimum actions would be defined. Cost optimum is different than cost effective; an action can be cost-effective while it is not cost-optimum. However, cost-optimum action should be a cost-effective action. A retrofit action is cost-effective when the cost of implementation is lower than the value of the benefits that result, taken over the expected life of the measure. While the cost-optimal scenarios represent that retrofit measures or combination of measures that have minimum global cost estimated economic lifecycle.

The primary energy consumption of a building is calculating by multiplying the end-use energy consumption of each component to the conversion factor of related fuel. The conversion factor is different from country to country. To define primary energy consumption amounts in Turkey, the primary energy conversion factors announced by Turkish Ministry of Environment and Urbanization and indicated in the draft version of Green Building Certification Guide should be used. It is 2.36 for electricity and 1

for another type of fuels. Following formula should be used to define primary energy consumption in Turkey: (3.1)

$$PEC = e_{naturalgas} + (2.36 \times e_{electricity}) + e_{fueloil} \quad (3.1)$$

Whereas:

- *PEC* is total primary energy consumption;
- $e_{naturalgas}$ is the sum of whole End-Use natural gas energy consumption;
- $e_{electricity}$ is the sum of whole End-Use electricity energy consumption;
- $e_{feuloil}$ is the sum of whole End-Use fuel oil energy consumption.

3.3 Establishment of the Retrofit Measures

The main aim of this section is to define the retrofit measures that are energy efficient. EPBD states that retrofit measure means a change to a building resulting in a reduction of the building's primary energy consumption. Based on national construction market's conditions, retrofit measures should be established. Energy efficiency measures shall be defined for all input parameters for the calculation that have a direct or indirect impact on the energy performance of the building. The combination of these measures should be determined as well. It is obvious that there are lots of measures that can be applied to the buildings. Hence, the number of calculations can exceed from the feasible amount. It is necessary to eliminate similar measures or measures that have similar cost and energy effects to reach a reasonable amount of calculations. EPBD obligates that existing national minimum energy performance requirements provide a base for retrofit measures. Thus, first of all, the measures that will lead the existing building's energy performance to reach the current national minimum energy performance requirements should be defined. TS825 standard that is an insulation standard and BEP-Tr are presenting some minimum energy performance requirements for Turkey. Hence, they should be focused in any study related to the EPBD subject in Turkey.

In general, retrofit measures can be categories in following four main items:

- Architectural System's Improvements: Improvements related to building enclosures (e.g. walls, windows, roofs),

- Mechanical System's Improvements: Improvements related to HVAC and Domestic Hot Water (DHW) systems,
- Lighting System's Improvements,
- Renewable Energy System's Application and/or Improvements.

The comprehensive national market analysis should be performed to define these measures. As the main objective of this study is to provide an economically applicable retrofit solution for existing residential buildings, more common retrofit solutions have a crucial role in the study. Some advanced renewable measures such as PV and solar collector application will be analyzed as EPBD requires it.

3.4 Carry Out of Energy-Cost Analyses for the Retrofit Measures

Energy and cost analyses should be done for defined retrofit measures to define the applicability of them. The main aim of this section is to define the cost-optimum scenario for energy efficient retrofit of the existing residential buildings. As indicated before, the measures can be divided into two main categories: single and combined measures. The numbers of combined measures would be high. It is time-consuming and absurd to apply all analyses to all of the combined measures if it is possible to define those that will not be cost-optimum. Thus, it is preferred to put some filtering during the analyses.

The combined measures that include a single measure that is not cost-effective would not be cost optimum. Thus, the first filtering can be performing by using the separate analyses for single measures. On the other hand, lighting system improvements and renewable system applications have no/a few impacts on the energy demand of the residential buildings' HVAC system while architectural, and mechanical system improvements have a close relation with it. Hence, it is possible to divide the combined measures to two main categories and apply the analyses to each of these categories separately: architectural and mechanical improvements, lighting system improvements and renewable energy applications. By using this method, the number of calculations will be decreased significantly.

Based on above statements, energy-cost analyses' methodology for single and combined measures has ten steps:

1. carry out energy analyses for the single retrofit measures,
2. carry out cost analyses for the single retrofit measures,
3. determination of the economically reasonable single measures,
4. carry out energy analyses for the combination of the reasonable single retrofit measures (except lighting improvements and renewable system application),
5. carry out cost analyses for the combination of the reasonable single retrofit measures (except lighting improvements and renewable system application),
6. determination of the economically reasonable combined measures (except lighting improvements and renewable system application) (ERCMs),
7. carry out energy analyses for the ERCMs with lighting improvements and renewable system application,
8. carry out cost analyses for the combination of ERCMs with lighting improvements and renewable system application,
9. determination of cost-optimum combined measures,
10. calculation of cost per flat for cost-optimum combined measures.

3.4.1 Carry out energy analyses for the single retrofit measures

Similar to the existing case study residential building, the energy analyses should be done for each retrofit measures and their combinations. The process to determine the primary energy consumption and CO_2 emission of each measure are entirely similar to the process indicated in section 3.2. EnergyPlus software can be used solely as the geometry (model) is similar to the existing case study residential building and just modification is necessary to apply to the existing model. Thus, DesignBuilder is not very useful in this section. However, if HVAC system modification includes any system changes, DesignBuilder software can be used. For example, the addition of solar collector to the HVAC system or replacement of individual heating system with central system requires a large modification in the model. Hence, DesignBuilder is more reliable than EnergyPlus to use in these matters.

To define the CO_2 emission related to each measure, the amounts of end-use energy consumption of the building under retrofit by each measure are multiplied by the conversion factors related to each fuel; the sum of these values are indicating total CO_2

emission. This conversion factor is also differing from country to country. The conversion factor for natural gas, electricity and fuel oil are 0.234, 0.626 and 0.33 respectively (Çedbik, 2013). Below formula should be used to define the CO_2 emission in Turkey: (3.2)

$$E_{CO2} = (0.234 \times e_{naturalgas}) + (0.626 \times e_{electricity}) + (0.33 \times e_{fueloil}) \quad (3.2)$$

Whereas:

E_{CO2} is total CO_2 emission;

$e_{naturalgas}$ is the sum of whole End-Use natural gas energy consumption;

$e_{electricity}$ is the sum of whole End-Use electricity energy consumption;

$e_{fueloil}$ is the sum of whole End-Use fuel oil energy consumption.

3.4.2 Carry out of cost analyses for the single retrofit measures

EN 15459 (Energy performance of buildings – economic evaluation procedure for energy systems in buildings) presents the most reliable calculation methods that are recommended by EPBD to use in cost-optimal analyses. There are two methods to use in cost calculations:

- Equivalent annuity method:

The annuity calculation method transforms any costs during a given timeframe to average annualized costs by the use of an annuity factor.

- Net present value:

The net present value (NPV) is a standard method for the financial assessment of long-term projects. This method that usually known as global cost method measures the excess or shortfall of cash flows, calculated at their present value at the start of the project.

The annuity calculation method transforms any costs to average annualized costs and results in a figure for annual costs. The global cost calculation method results in a present value of all costs during a defined calculation period (e.g. 30 years), taking into account the residual values of equipment with longer lifetimes.

From these methods, the net present value (NPV) is recommended by EU Commission Delegated Regulation to use (EU Commission, 2012). Calculation period for residential buildings should be set to 30 years as is obligated by that regulation as well. It is also stated that the "global costs for buildings and building elements shall be calculated by summing the different types of costs and applying to these the discount rate using a discount factor so as to express them regarding value in the starting year, plus the discounted residual value."

3.4.2.1 Categorisation of costs

There are four main categories for costs in global cost calculation method: initial investment cost, annual cost, disposal cost and cost of greenhouse gasses (or carbon). Disposal cost is not applicable when it is expected that the building will be standing after the conclusion of the calculation period. The cost of the greenhouse shall apply when studying in macroeconomic level. Figure 3.2 is indicating the cost categorization according to the cost-optimal framework methodology (Figure 3.2).

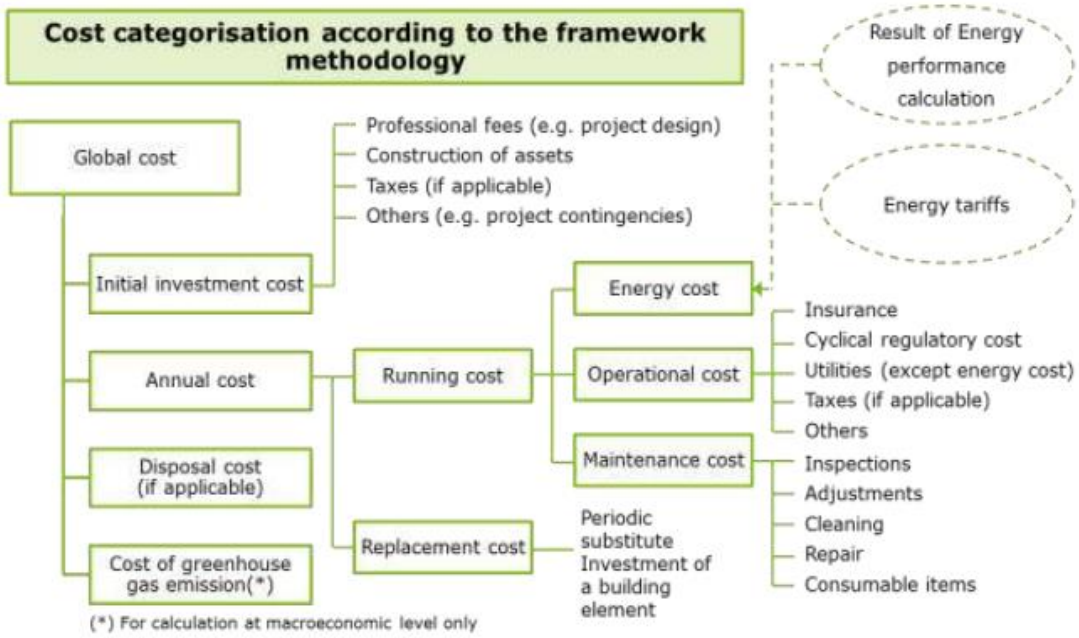

Figure 3.2 : The Cost Categorisation According to the Cost-Optimal Framework Methodology (Ecofys, 2015).

It is crucially important to note that the cost of actions that are not necessary from energy performance point of view should not be included in the calculation. For example, when interior render of a unit is destroyed and necessary to renew, the cost of a related action should not be included in the calculation as it is not affecting the

energy performance of the building. This means that carpets, interior doors, roof tiles etc. in general construction products, load-bearing structures, and components that do not have a substantial impact on the energy performance, are not included in the cost calculation.

For a proper financial assessment, the following financial data for different measures applied to the case study residential building should be gathered:

- energy related improvements' costs (insulations, windows, HVAC system, lighting, renewable energy, controls, etc.),

- periodic costs of components' replacements,

- corresponding costs for maintenance, operation and additional costs,

- energy costs (price of energy as paid by the customer).

The sum of all of these expenses should be depreciated by the sum of the residual values of the building's components undergo retrofit at the end of the calculation period that is 30 years in this study. The residual value shall be determined by a straight-line depreciation of the initial investment or replacement cost of a given building component until the end of the calculation period discounted to the beginning of the calculation period.

3.4.2.2 Calculation of the initial investment cost

The cost data must be based on a coherent market analysis. An evaluation of recent construction projects, an analysis of standard offers of construction companies, or existing cost databases which have been derived from market-based data gathering could provide a base for calculation.

In general, the initial investment cost can be divided into three main categories: direct cost (materials, transportation and labor), indirect cost (infrastructure, contractors benefits, overheads and so on) and TAXs. To determine the direct cost of materials it is more reliable if the average cost from three construction material provider companies is obtained. If the cost of labor and transportation are provided by those companies, it is not necessary to collect them separately. Otherwise the cost for labour and transportation should be obtained from other sources.

In Turkey, 25% of whole direct costs are assumed to be equal to indirect costs. Indirect costs, as purposed in national regulations, include the cost of any required infrastructure, contractor benefits, overheads and so on. However, there is controversial idea about the inclusion of infrastructure in the indirect cost, in this study it is assumed that this cost is included in the 25% of the direct cost.

To determine the applicability of each single and combined measures, it is necessary to define the amount of money that should be paid by each flat owner. These costs are defined by dividing the initial investment cost related to each measure to the number of flat in each building.

3.4.2.3 Calculation of annual costs

Annual costs include the replacement costs and the running costs.

Calculation of the running cost

Running cost is an annual cost comprising maintenance costs, operational costs, energy costs. Following equation should be used to define the running cost Cy(τ): (3.3)

$$\mathrm{Cy}(\tau) = Cm + Co + Ce \tag{3.3}$$

Where,

Cm is total maintenance cost during the calculation period,

Co is total operating cost during the calculation period,

Ce is total energy consumption cost during the calculation period.

The maintenance cost is comprising the annual costs for measures for preserving and restoring the desired quality of the component. This includes annual costs for inspection, cleaning, adjustments, repair under preventive maintenance, consumable items. Consider staff inspection and consumable items or annual contracts for cleaning and maintenance of components and systems. As periodic inspection of energy systems for heating and air conditioned systems are mandatory, the costs related to these actions should be included in maintenance costs. Annex A of EN 15459 provides value for annual preventive maintenance cost including operation, repair and servicing in percentage of the initial investment cost. By multiplying those value to the initial investment cost of each component, the amount of yearly maintenance cost for that

component will be defined. The amount of yearly maintenance cost should be multiplied by the present value factor of the component for the calculation period of n (Pv(c,n)). (3.4)

$$Pv(c,n) = \frac{1 - \left(1 + \frac{RI}{100}\right)^{-n}}{\frac{RI}{100}} \tag{3.4}$$

When RI is the real interest rate that is related to the market interest rate (R) and the inflation rate (Ri). The market interest rate and the inflation rate both may differ in the year i compare to the current rate, but it is assumed in EN 15459 to be constant. The formula to calculate real interest rate related to the energy carriers is as following: (3.5)

$$RI = \frac{R - Ri}{1 + \frac{Ri}{100}} \tag{3.5}$$

The operational costs represent the cost for energy operators of the building. Insurance, utility, cyclical operations and related TAXs should be calculated under this cost. If the cost is equal for all measures this cost could be eliminated.

The energy costs should be calculated based on the end-use energy consumption of the building's energy systems. The result of energy calculation in section 3.4 should be used to define the energy cost. At least average of the last five years' tariffs for each energy carrier should be used in calculations. Based on national distributors announced rate, the average of the last five years' tariff for electricity, natural gas and fuel oil in Turkey are 0.366371, 0.1097754 and 0.1657 TL/kWh including TAX respectively. By multiplying these amounts to the related end-use energy consumption of each component, the yearly cost of energy consumption in the starting year will be defined.

The whole energy cost (Ce) for the calculation period should be calculated according to the following formula: (3.6)

$$Ce = Ce(i) \times Pv(e,n) \tag{3.6}$$

When:

Ce(i) means the total yearly cost of energy at the starting year,

Pv(e,n) means the present value factor of energy for the calculation period of n.

To calculate the present value factor of the energy, formula 3.4 should be used.

Calculation of the replacement cost

To define the replacement cost, it is necessary to obtain the lifespan of each building components. The lifetimes of some building's components are indicated in Annex A1 of EN15459, for the rest of the components experts' suggestions, and literature reviews should be used. Periodic cost related to components' replacements, Cr(τ), should be calculated based on these values. The following formula should be used to derive the cost of each replacement: (3.7)

$$\mathrm{Cr}(\tau) = CI \times \left(1 + \frac{Rd\ (i)}{100}\right)^{Lp} \tag{3.7}$$

When:

CI means initial investment costs for measure or set of measures,

Lp is the lifespan of the product.

Rd (i) means discount rate for the application year (i) and should be calculated as follows: (3.8)

$$Rd(i) = \left(\frac{1}{1 + \frac{RI}{100}}\right)^{p} \tag{3.8}$$

When *p* means the number of years from the starting period of the replacement time and *RI* means the real interest rate.

If a building's component should be change two or more times during the calculation period, the cost of each replacement should be calculated separately.

3.4.2.4 Calculation of the global cost

Global costs for buildings and their components should be calculated by summing the related costs and applied to these the discount rate using a discount factor to express them regarding value in the starting year, plus the discounted residual value as follows: (3.9)

$$\mathrm{Cg}(\tau) = CIn + \sum_j [\sum_{i=1}^{\tau} \big(Cy(\tau) + Cr(\tau)\big) - Vf,\tau(j)] \tag{3.9}$$

When,

τ means the calculation period

Cg(τ) means global cost (referred to starting year 0) over the calculation period,

CIn means initial investment costs for measure or set of measures j,

Cy(τ) means running cost during calculation period for measure or combination of measures,

Vf,τ (j) means residual value of measure or set of measures j at the end of the calculation period,

The residual value that is the value of components at the end of the calculation period, considering their lifespan and referred to the starting year, should be calculated as following: (3.10)

$$Vf,\tau(j) = Clr(\tau) \times \frac{Lp-\tau}{\mathrm{Lp}} \times Rd(\tau) \qquad (3.10)$$

When,

Clr(τ) represents the cost of last replacement,

$\frac{Lp-\tau}{\mathrm{Lp}}$ represents the linear depreciation of the last replacement cost,

Rd(τ) represents the discount rate at the end of the calculation period.

3.4.2.5 Calculation of the payback period of the measures

Sometimes measures that are cost-effective have a very high payback period. Implementation of such measures are irrational and it's necessary to determine and exclude them. Simple payback calculation method can provide an overview of what happened after application of the measures. Low payback time can be encouraging for flat owners. Recent studies and funds in EU are oriented towards using the measures with low payback time. Simple payback time (Pt) can be defined by multiplying the amount of initial investment cost to the energy cost saving (Case). (3.11)

$$Pt = \left(\frac{CI}{Cse}\right) \qquad (3.11)$$

Measures that have high amount of payback time should be excluded from further analysis to have applicable retrofit scenarios.

3.4.3 Determination of the economically reasonable single measures

To define the economically reasonable single measure/measures, it is necessary to draw a graph that indicates the relation between building energy consumptions and global costs under retrofit by different single measures. Such a graph is recommended by EPBD and other supplementing documents and has the global cost on its Y-axis and primary energy consumption on its X-axis. Pre-retrofit location of existing building together with the post-retrofit location of it by different retrofit measures are indicated on the graph. The lowest point of the graph that indeed has the lowest global cost is the cost-optimum point. Some nearby measures should also be defined as cost-optimal measures. In case that some scenarios have more or less equal global cost, the measure that has lower primary energy consumption is the cost-optimum scenario. Indeed, these points deliver the best energy and environmental performance at the lowest cost. The measures that have lowest primary energy consumption on this graph are nearly zero energy buildings (NZEB). (Figure 3.3)

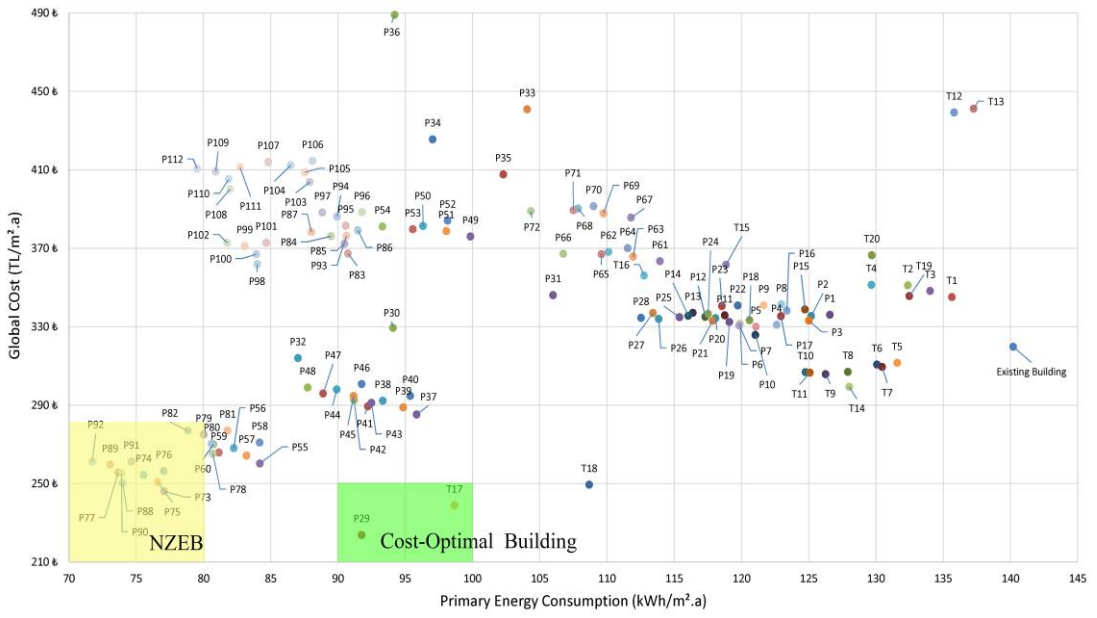

Figure 3.3 : A sample of Global Cost vs. Primary Energy Consumption graph.

As the main aim of this study is to define economically applicable solutions for energy efficient retrofit of the existing residential buildings, this graph plays a crucial role during the analysis. Results of section 3.4 and 3.5 will indicate the points on the graph.

Previous studies are indicating that combinations of measures have lower global cost than existing building if each of the combined single measures have lower global cost than existing building separately. Thus, it is absurd to use the single measures that have higher global cost than the existing building, and these measures will not be included in the cost-optimum scenarios. The aim of this step is to reduce the number of calculations by determining the economically applicable single measures. After related graph is drawn, some single measures can be excluded from further analyzed and the number of calculations will be decreased.

Together with above-mentioned measures, the measures that have a high amount of payback period and cost per flat are not reasonable and should be excluded from further analyses. Cost per flat can be defined by dividing the investment cost to the number of flats available in each building as indicated in section 3.4.2.2. To define the acceptable amount of cost by flat owners, a literature study is conducted. According to TÜİK statistics, the average yearly income for households with median income in Turkey was 22752 TL in 2013. By considering 8.8% inflation rate, the average income for a median household should be 29087 TL in 2015. In average 25% of household expenditure in Turkey is belonged to housing rent and maintenance. If an owner consumes the whole of its yearly income, it means that it consumes about 7272 TL for housing. Based on Republic of Turkey's Ministry of Energy and Natural Resources, on average, a household paid about 73 TL for electricity and 135 TL for natural gas monthly. It means the whole yearly amount of housing bill for households is about 2496 TL. Rest of housing related expenditure of a household that is 4776 TL can be invested by an owner on renovation actions. Also, for one rank lower income households' group, this amount is 2270 TL. Thus, it can be assumed that each flat owner can invest about 2270 TL per year for the retrofit action, and 2270 TL cost per each flat owner is reasonable for each retrofit action. The measures with higher than about 2270 TL cost per flat should be divided into steps with reasonable cost or apply with the one-year postponement. Measures with more than about 4540 TL cost per flat should be excluded from further analyses.

3.4.4 Carry out energy analyses for the combination of the reasonable single measures (except lighting improvements and renewable system applications)

After determining the economically applicable single measures and filtering unreasonable single measures, a combination of the single reasonable measures should be established and analyzed. To prevent from unnecessary calculations, lighting improvements and renewable system applications are excluded from initial combinations. A similar process for single measures that are indicated in section 3.4.1 should be applied to these combined measures.

3.4.5 Carry out cost analyses for the combination of the reasonable single measures (except lighting improvements and renewable system applications)

Cost analyses for a combination of single reasonable measures except lighting improvements and renewable system applications should be done in this section. The similar process indicated in section 3.4.2 should be apply to define the cost of the combination of the reasonable single measures (except lighting improvements and renewable system applications).

3.4.6 Determination of economically reasonable combined measures (except lighting improvements and renewable system applications) (ERCMs)

After concluding the energy and cost analyses for a combination of economically applicable single measures except lighting improvements and renewable system application, these measures should be located in global cost vs. primary energy consumption graph. The actions that are located in the lowest part of the graph are ERCMs.

3.4.7 Carry out energy analyses for the combination of the ERCMS with lighting improvements and renewable system applications,

After determination of ERCMs, it is time to combined them with lighting improvements and renewable system applications. As energy analyses, the process indicated in section 3.4.1 should be applied to these combined measures. The primary energy consumption of each combination should be determined separately to locate in global cost vs. primary energy consumption graph.

3.4.8 Carry out cost analyses for the combination of the ERCMS with lighting improvements and renewable system applications,

The global cost of the combinations of ERCMs and lighting improvements and renewable system applications should be determined separately based on the process indicated in section 3.4.2 to locate in global cost vs. primary energy consumption graph.

3.4.9 Determination of the cost-optimum measures

By concluding the calculation process of global cost and primary energy consumption of single and combined measures, it is time to draw the global cost vs. primary energy consumption graph for the whole of the reasonable actions and locate them on the graph. The lowest points of the graph are cost-optimum measures of the retrofit action. These actions have the lowest global cost during the calculation period that is 30 years for residential buildings according to EPBD-Recast. Indeed, the measures with the lowest global cost are measures that in compare between costs of losses and profits, the profits have more weight, while having reasonable energy consumption. Hence, these measures contain the optimum actions from cost and energy consumption points of view.

3.4.10 Calculation of cost per flat for the cost-optimum measures

Cost per flat for the cost-optimum combined measures should be calculated by dividing the total initial investment cost of the related measures to the number of flat in each building.

The applicability of cost-optimum combined measures should be analyzed using the cost per flat. If these measures compel each flat owner to pay less than reasonable cost, then they can carry out as one step action. If they require a higher budget, they are not applicable from a cost point of view, and further analyses are necessary as they would not be acceptable by most of the flat owners.

3.5 Determination of Proper Step-By-Step Retrofit Scenarios and Carry Out of the related Energy-Cost Analyses

It is obvious that any measure with high investment cost per flat owner would not be applicable. To increase the applicability of the retrofit actions and improve the yearly

retrofit rate, it is necessary to make the actions attracting for the owners. Low amount of yearly retrofit rate is indicating that current process of retrofit actions are not attractive for owners. To increase the applicability and attractivity of the retrofit actions, step-by-step scenarios could be useful. By using this method, it is possible to apply the retrofit actions without any financial instrument. The owners can act as financiers for their actions.

The calculation methodology that should be used in this section is more or less similar to section 3.4, with the difference that there is a time lag among application of measures. This time lag is affecting the energy consumption, investment cost, replacement cost, and all other expenses. The time lag should be considered during all of the calculation process. This time lag would lead to increase in the global cost and primary energy consumption of the building under retrofit by the step-by-step scenarios. Hence it is necessary to define the amount of loss to determine whether they are applicable or not.

This section's methodology includes following steps:

1. determination of steps' order for step-by-step scenarios,
2. calculation of the average primary energy consumption of the buildings under retrofit by step-by-step scenarios,
3. calculation of the global cost of the buildings under retrofit by step-by-step scenarios,
4. determining the losses for step-by-step scenarios.

3.5.1 Determination of steps' order for step-by-step scenarios

To make the initial investment cost of cost-optimum measures reasonable for owners, it is inevitable to divide them to some steps with rational payments. The numbers of possible scenarios depend on the number of measures that are included in the action. It is assumed that each flat owner can pay about 2270 TL per year for the retrofit action of the buildings. Measures with more than this amount but less than about 4540 TL should be applied by one-year postponement to be sure that owners can provide required initial investment cost for the action.

In this study, two different scenarios are going to be investigated. The first scenario's steps are based on the cost per flat while the second scenario's steps are based on the

primary energy saving of each single measure. The first scenario starts with the measures that provide the lowest cost per flat. The second scenario starts with the measure that provides the most primary energy saving for the building.

3.5.2 Calculation of the average primary energy consumption (PEC) of the buildings under retrofit by step-by-step scenarios

To determine the average PEC of the buildings, it is necessary to perform related simulations indicated in section 3.4.1 separately for each single measure by applying the previous steps improvements. For instance, to calculate the PEC of the second step, the improvements in the first step should be implemented together with second step's enhancements. After concluding all required calculations, the results should be multiplied by the duration of each step (the number of years that each step will be available in the building) and divided by calculation period. The last steps duration is total calculation period minus last steps application year. Thus, the following formula should be used to calculate the average PEC: (3.12)

$$PEC = \frac{(PEC1 \times d1) + \cdots + \left(PEC(n-1) \times d(n-1)\right) + \left(PECn \times \left(\tau - \left(d1 + d1 + \cdots + d(n-1)\right)\right)\right)}{\tau} \qquad (3.12)$$

When,

(1,…,n) are indicating the number of each step,

$PEC_{(1\ldots n)}$ is PEC of the building during each step,

$d_{(1\ldots n)}$ is the duration of each step,

τ is calculation period

3.5.3 Calculation of the global cost of the buildings under retrofit by step-by-step scenarios

As the cost calculation method is based on net present value method, all costs should be modified to show the value based on present costs. The method to calculate different costs related to the step-by-step application are indicated below:

3.5.3.1 Calculation of the initial investment cost for step-by-step scenarios

The initial investment cost for each step ($CIn(s_n)$) at the application time (T) should be based on present initial investment cost (CIn(p)) and calculated based on the following formula that is adopted from formula 3.7: (3.13)

$$CIn(s_n) = CIn(\mathrm{p}) \times \left(1 + \frac{Rd\ (i)}{100}\right)^{T} \qquad (3.13)$$

3.5.3.2 Calculation of the annual cost for step-by-step scenarios

To calculate the running cost of step-by-step scenarios, the yearly maintenance cost related to each component and annual energy carriers' costs should be calculated separately for pre and post retrofit condition. Then each of these amounts should be multiplied by the pre and post retrofit's present value factor. Total of these costs and the replacement costs are total annual cost. The replacement cost should be calculated based on formula 3.8.

The formula to calculate the present value factor to use in maintenance cost and each step's energy cost's calculation is as follows: (3.14)

$$Pv(e,n) = \frac{1-\left(1+\frac{RI}{100}\right)^{-n}}{\frac{RI}{100}} * Rd\ (i) \qquad (3.14)$$

When Rd(i) is the discount rate for application year, n is the duration of the step and RI is the real interest rate.

3.5.3.3 Calculation of the global cost for step-by-step scenarios

The process to calculate the global cost is similar to the process indicated in the section 3.4.2.4 with this exception that the residual value for each component should be calculated separately for pre and post retrofit.

3.6 Undertaken Sensitivity Analyses for Economic Variations

It is obligated by EPBD-Recast to undertake sensitivity analyses for economic variations. Sensitivity analysis for at least two different interest rates one of which shall be 3% expressed in real terms is required by commission delegate regulation. It

is stated by that regulation that “cost calculations and projections with many assumptions and uncertainties, including for example energy price developments over time, are accompanied by a sensitivity analysis to evaluate the robustness of the key input parameters”. The sensitivity analysis allows assessing how final results may change according to the variation of assumptions and key economic parameters, on which the related calculation is based. Thus, the sensitivity analyses for two different discount rate would be undertaken during this study.

4. ECONOMICALLY APPLICABLE ENERGY EFFICIENT RETROFIT SOLUTIONS FOR CASE STUDY RESIDENTIAL BUILDINGS IN TURKEY

To verify the methodology defined in the previous chapter, case study analyzes are carried out. Two case study buildings are selected among 26 reference buildings determined for Turkey through a TÜBİTAK supported project stated in 2.7.3. From five different climatic zones available in Turkey, three mostly different climatic zones are selected. Case study analyses performed in these three distinct climatic zones. Three representative cities are chosen in these climatic zones. Istanbul, Antalya, and Erzurum represent mild-humid, hot-humid and cold climates respectively. Indeed, a city in a mild climate, another in a hot climate and the last one in a cold climate are selected to verify the methodology of the research study. Most of the cities around the country have similar climatic conditions to these representative cities, hence by concluding the study, an overview of national buildings' potential would be obtained.

The case study buildings are representing the row and detached apartment buildings that are widespread building types in Turkey. These reference buildings contain most common buildings'charachteristics in building market. Architectural, mechanical and lighting characteristics together with user profile are defined based on construction market analyzes carry out in related TÜBİTAK supported the project.

Retrofit measures are also defined based on market analyzes. Most common retrofit scenarios are taken into account. Required construction details are provided according to experiences obtained from construction market.

Then, energy and cost analyses are done for related six buildings, a couple of buildings in three climates, to define the cost-optimal actions. Cost per flat is compared with the reasonable amount. By applying the step-by-step scenarios to the cost-optimal measures, the amount yearly payment for each owner is reduced to the reasonable amount and related analyses are done in the following parts.

The sensitivity analyses are done in the last part of this section to assess how final results may change by variation of assumptions and key economic parameters, on which the methodology is based.

4.1 Climatic Analyses of Representative Cities

In general, there are five different climatic zones in Turkey. Cold, mild-humid, mild-dry, hot-humid and hot-dry are these climatic zones. In general, three climatic zones can represent whole Turkey: cold, hot and mild. Istanbul, Antalya, and Erzurum that are three big cities in Turkey are representing mild-humid, hot-humid and cold climates respectively in this study (Figure 4.1).

Figure 4.1 : Climatic zones of Turkey and location of the representative cities.

Istanbul is a city with a climate affected by Marmara Sea that has cold winters with low temperatures averaging 1–4 °C. Lake-effect snow from the Black Sea is common, although difficult to forecast. Numbers of snowy days is less than ten days per year. Springs and autumns are mild but often wet and unpredictable; chilly winds from the northwest and warm gusts from the south tend to cause fluctuations in temperature. Antalya has a hot-summer Mediterranean climate with hot and dry summers and mild and rainy winters. More than 3/4 of days per year are sunny, with nearly 3,000 hours of sunlight per year. Erzurum has a cold climate with cold, snowy winters and warm, dry summers along with chilled nights. The average minimum daily temperature

during January is around −15 °C. Sometimes temperatures fall even below −30 °C in most of the years.

4.2 Case Study Residential Buildings

As indicated in section 2.7.3, in the related TÜBİTAK supported study, 26 buildings belonging to 3 different time periods in three main categories (Single Family Houses, Standard Apartments, and High-Rise Luxury Residences) were defined as reference residential buildings in Istanbul. These buildings could be developed to all over Turkey. Two of those reference buildings are chosen as case study residential buildings in this thesis study. One of them is representing detached housing system, and the other one is representing row housing system. Row and detached housing systems are mostly representative systems for Turkey's residential building stock. Building geometry is the same in all of the related climates while envelope properties are different due to different mandatory requirements that are prescribed in TS825 standard which is an obligatory insulation standard for buildings in Turkey.

The case study detached building is constructed between 1985 and 1999 based on that period's legislations. This 6-floor building (5 occupied floor and an underground floor) has a gross area about 2729 m^2, from this amount 415 m^2 is belonged to the sloped roof area that is unoccupied. The building has three dwelling units on each floor with about 120 m^2 and 130 m^2 area. The case study row building also has five occupied floors and an underground floor that constructed between 2000 and 2008 with a flat roof. Each unit has three bedrooms and one living room. The height of each unit is 2.7m from above to below floor and 3m from floor to floor. Most of the living areas are faced to The South. Figure 4.2 is showing the plan drawings and 3D views of case study reference buildings (Figure 4.2).

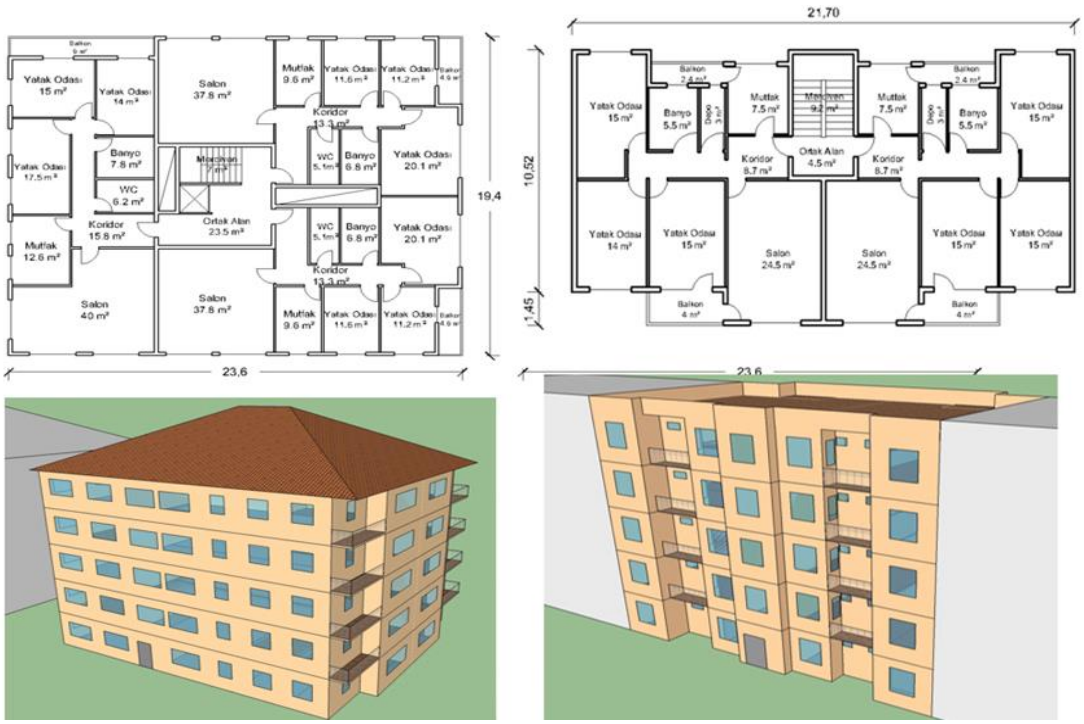

Figure 4.2 : Drawings and 3D views of case study reference buildings.

4.2.1 Physical and Thermo-Physical Properties

The physical and thermo-physical properties of the case study residential buildings extracted from architectural and mechanical systems' characteristics are indicated in the following sections for the detached and row buildings:

4.2.1.1 Detached buildings

As the construction period of this building is between 1985 and 1999, the building's materials U-values are chosen from the TS825-1985 standard. As there isn't any information related to SHGC of glazing systems in that standard, SHGC is selected from Bep-Tr regulation. It is estimated that glazing system of this building is renovated once and changed to the double glazing system. Table 4.1 is representing general characteristics of building materials for detached building located in each climate separately (Table 4.1).

Table 4.1 : General features of the detached case study building's materials.

	Exterior Wall	Roof	Ground Floor	Glazing System
U-value ($W/m^2°K$) - Istanbul	1.37	0.77	1.25	2.8
U-value ($W/m^2°K$) - Antalya	2.3	0.96	1.8	2.8
U-value ($W/m^2°K$) - Erzurum	1	0.49	0.75	2.8

Based on a setpoint temperature provided by EN ISO 15251-2007 and Building Energy Performance of Turkey (BEP-TR), the setpoint temperature for heating and cooling is set to 20°C and 26°C respectively. Moreover, the heating system of the building is a diesel based central boiler, with 0.8 "Nominal Thermal Efficiency", supported by an internal radiator (Baseboard Hot Water Convector). The cooling system is an individual system supported by packaged air-conditioner units. The efficiency of the cooling system is set to 2.4 COP. The mechanical ventilation system is not used in the building, and only natural ventilation is at work. Based on Bep-tr regulation, the infiltration rate is set to 0.5 ACH. The Domestic Hot Water (DHW) system is the electrical heater system. Table 4.2 includes the characteristics of building HVAC systems (Table 4.2).

Table 4.2 : Detached buildings' HVAC systems' characteristics.

Heating System	Central Boiler
Heating Equipment	Internal Radiator (Baseboard Hot Water Convector)
Heating System Fuel	Diesel
Cooling System	Individual System (Packaged Air-Conditioner Unit)
Cooling System Fuel	Electricity
Ventilation System	Natural
DHW System	Electrical Heater

4.2.1.2 Row buildings

The construction period of this building is between 2000 and 2005. Hence, the building's materials U-values are chosen from TS825-2000 standard. As there isn't any information related to SHGC of glazing systems in that standard, SHGC is selected from Bep-Tr and TS825-2013 regulations. Table 4.3 is representing general characteristics of building materials for row building located in each climate separately (Table 4.3).

Table 4.3 : General features of the detached case study building's materials.

	Exterior Wall	Roof	Ground Floor	Glazing System
U-value ($W/m^2°K$) - Istanbul	0.6	0.4	0.6	2.6
U-value ($W/m^2°K$) - Antalya	0.8	0.5	0.8	2.8
U-value ($W/m^2°K$) - Erzurum	0.4	0.25	0.4	2.4

The setpoint temperature for cooling and heating is set to 26°C and 20°C respectively. The heating system of each unit is a natural gas based combi-boiler, with 0.75 "Nominal Thermal Efficiency", supported by an internal radiator (Baseboard Hot

Water Convector). The cooling system is an individual system supported by packaged air-conditioner units. The efficiency of the cooling system is set to 2.6 COP. The mechanical ventilation system is not used in the building, and only natural ventilation is at work. Based on Bep-tr regulation, the infiltration rate is set to 0.5 ACH. The Domestic Hot Water (DHW) is provided by the combi boiler. Table 4.4 includes the characteristics of the building's HVAC systems (Table 4.4).

Table 4.4 : Row buildings' HVAC systems' characteristics.

Heating System	Combi Boiler
Heating Equipment	Internal Radiator (Baseboard Hot Water Convector)
Heating System Fuel	Natural Gas
Cooling System	Individual System (Packaged Air-Conditioner Unit)
Cooling System Fuel	Electricity
Ventilation System	Natural
DHW System	Combi Boiler

4.2.2 Lighting System's Characteristics

Interior lighting is defined based on market analysis. According to this analysis, it is considered that all lamps are 20W Compact Fluorescent Lamps (CFL) with 1150 Lumen luminous flux. Table 4.5 indicates the power of lighting system in the building (Table 4.5). It is estimated that during occupancy hours except sleeping hours when the illumination level provided by natural lighting is less than required amount (200 lux for bedrooms and 150 lux for the living room), the lighting system is on otherwise the system is off. Also, it is estimated that the lighting system is active diurnally in the kitchen for 4 hours and in other spaces for 2 hours.

Table 4.5 : The power of lighting system in the building.

Space	Lighting Power (W/m^2)	Space	Lighting Power (W/m^2)
Kitchen	8	Master Bedroom	5
Living Room	6.5	Other Bedrooms	9
Corridor	4	Bathroom	5

4.2.3 User Profile

The occupancy rate of the buildings is based on TUIK statistics. The occupancy rate of the buildings was determined based on Turkish Statistical Institute (TUIK) statistics. The average household member rate in Turkey is 3.7. Thus, it is assumed that two parents with two children currently live in each unit. Based on those statistics,

it is assumed that the wife is the matron. Table 4.6 indicates the occupancy rate for weekdays. (Table 4.6) Activity levels are based on ASHRAE Handbook of Fundamentals 2009. It is estimated that during the weekends between 12:30 – 15:30 all occupants are outside of the building and no one is at home. (Table 4.7)

Table 4.6 : Occupancy rate, activity, and activity level of each unit during weekdays.

Hours	Occ. No.	Activity	Act. Level (W/m^2)	Space
00:00 - 07:00	4	Sleeping	40	Bedrooms
07:00 – 07:30	4	Breakfast	60	Kitchen
07:30 -12:30	1	Home works	115	Whole Spaces
12:30 – 15:30	1	Reclining	45	Living Room
15:30 -16:30	1	Home works	115	Whole Spaces
16:30 – 19:00	3	1 person: Home works 2 person: Reclining	115 45	Whole Spaces
19:00 – 20:00	4	1 Person: Home works 3 Person: Sitting, Reading	115 60	Kitchen Living Room
20:00 – 20:30	4	Dinner	60	Kitchen
20:30 – 23:00	4	Sitting, Reading	60	Living/Bedrooms
23:00 – 24:00	4	Sleeping	40	Bedrooms

Table 4.7 : Occupancy rate, activity, and activity level of each unit during weekends.

Hours	Occ. No.	Activity	Act. Level (W/m^2)	Space
00:00 – 00:30	4	Sitting, Reading	60	Living/Bedrooms
00:30 – 08:30	4	Sleeping	40	Yatak Odaları
08:30 – 12:30	4	Sitting, Reading	60	Living/Bedrooms
12:30 – 15:30	0	Outdoor Activities	-	-
15:30 – 18:30	2	Sitting, Reading	60	Living/Bedrooms
18:30 – 22:30	3	Sitting, Reading	60	Living/Bedrooms
22:30 – 24:00	4	Reclining	45	Living/Bedrooms

4.3 Energy Performance of the Case Study Residential Buildings Located in the Representative Cities

The buildings are modeled using above mentioned characteristics in DesignBuilder and then exported to the EnergyPlus, and the energy analyses and calculations are done. In the following sections, the energy performance of existing row and detached buildings in each of related climates are illustrated.

4.3.1 Detached Building

Results of energy analyses for the existing detached buildings are as follows:

4.3.1.1 Results of energy analyses for the existing detached building located in Antalya

Results of the existing building simulations in Antalya's climate shows that most of the PEC of the case study reference building belong to cooling. After cooling that consumes 45% of whole 154.86 kWh/m^2.a primary energy, heating, and DHW are located. They are account for 18% of whole PEC. The lighting system is consuming 17% of total yearly primary energy. Pumps and fans are accounts for just 2% of PEC (Figure 4.3).

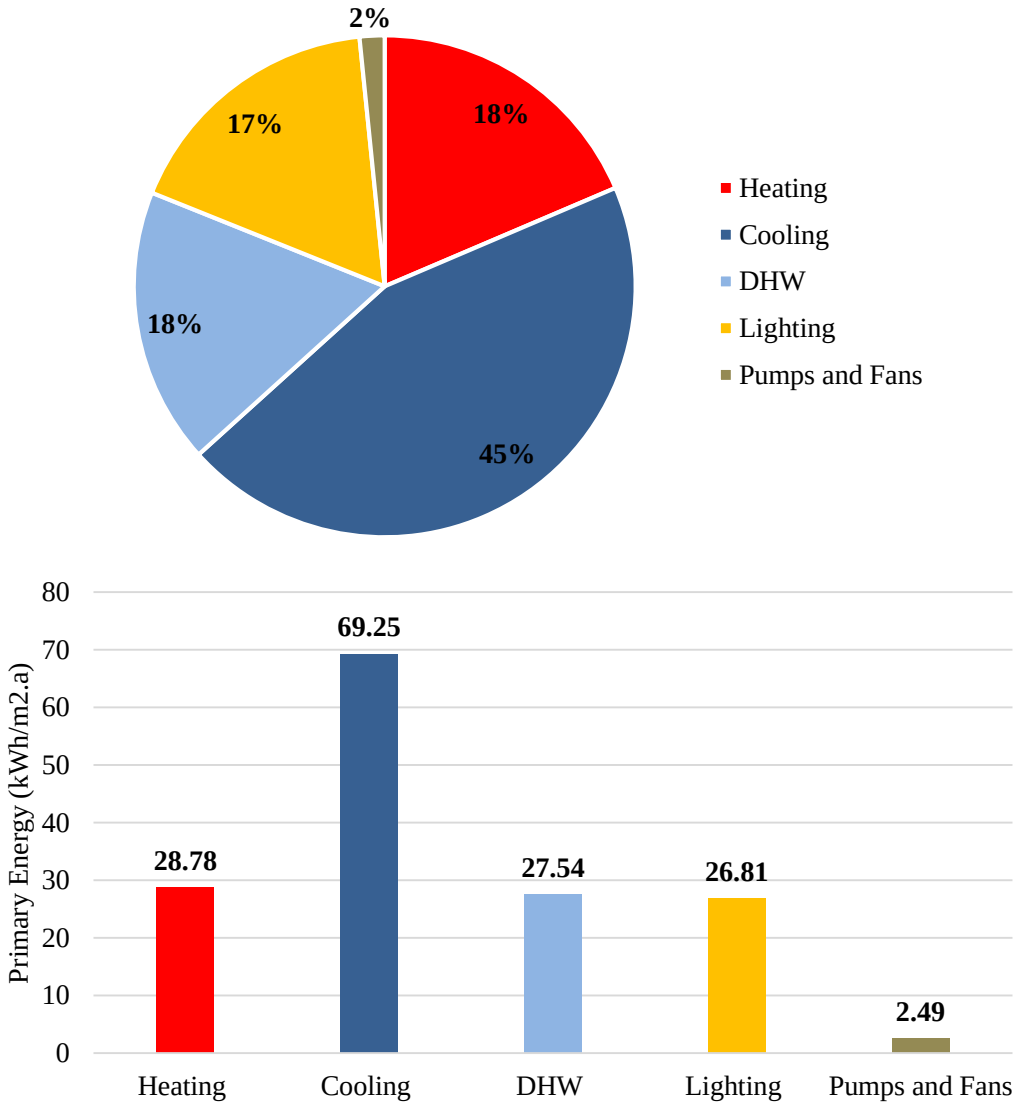

Figure 4.3 : Distribution of yearly PEC of the case study detaced building located in Antalya.

4.3.1.2 Results of energy analyses for the existing detached building located in Erzurum

Results of the existing building simulations in Erzurum's climate illustrates that most of the Primary Energy Consumption (PEC) of case study reference building belong to heating. After heating that consumes 66% of whole 195.03 kWh/m^2.a PEC, lighting, and DHW are located respectively. They totally account for 29% of whole PEC. The cooling system is consuming just 4% of total yearly primary energy (Figure 4.4).

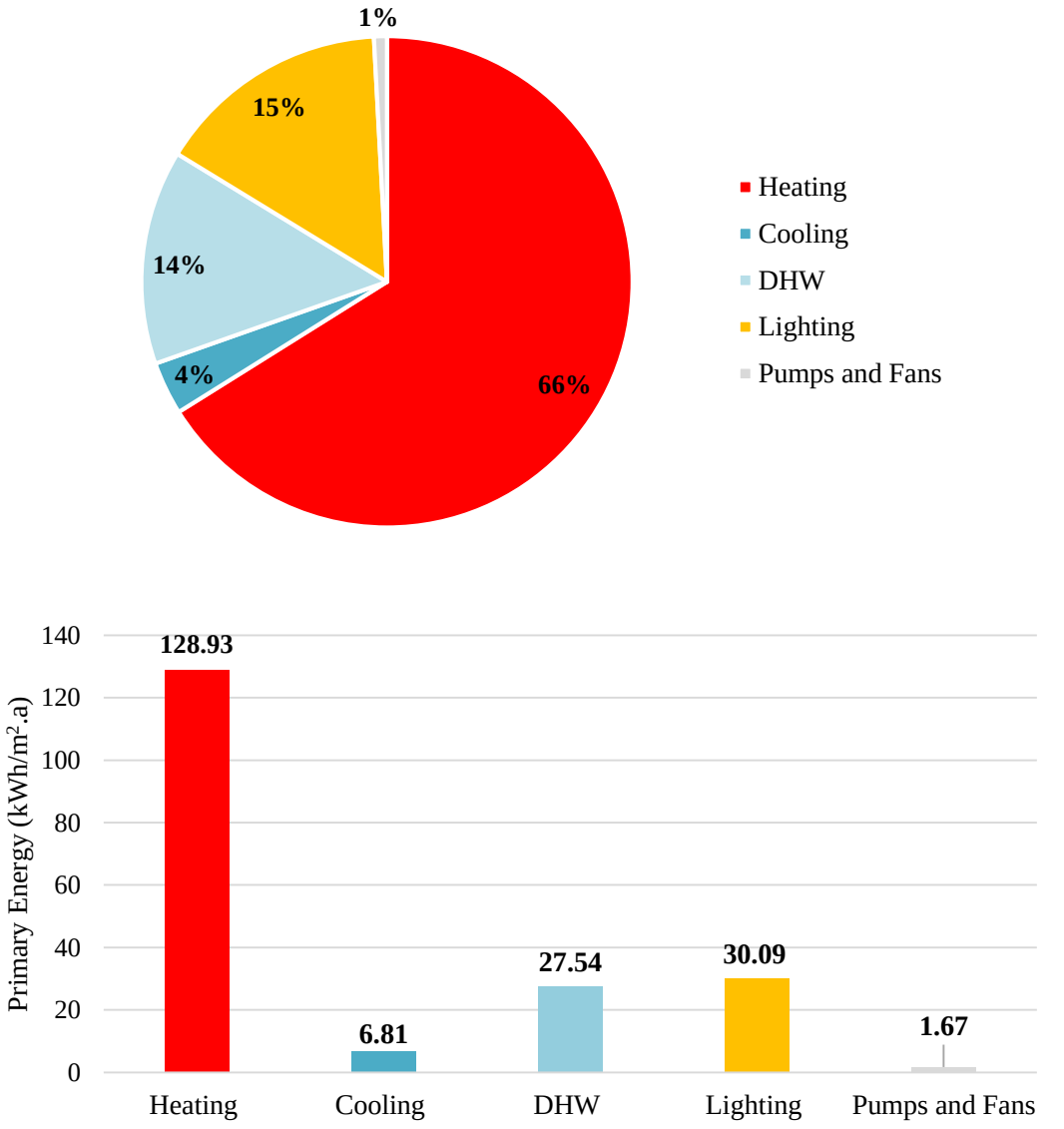

Figure 4.4 : Distribution of yearly PEC of the case study detached building located in Erzurum.

4.3.1.3 Results of energy analyses for the existing detached building located in Istanbul

Results of the existing building simulations in Istanbul's climate shows that most of the Primary Energy Consumption (PEC) of case study reference building belong to heating. After heating that consumes 45% of whole 143.17 kWh/m^2.a PEC, lighting, and DHW are located. They are account for 19% of whole PEC. The cooling system is consuming 16% of total yearly primary energy (Figure 4.5).

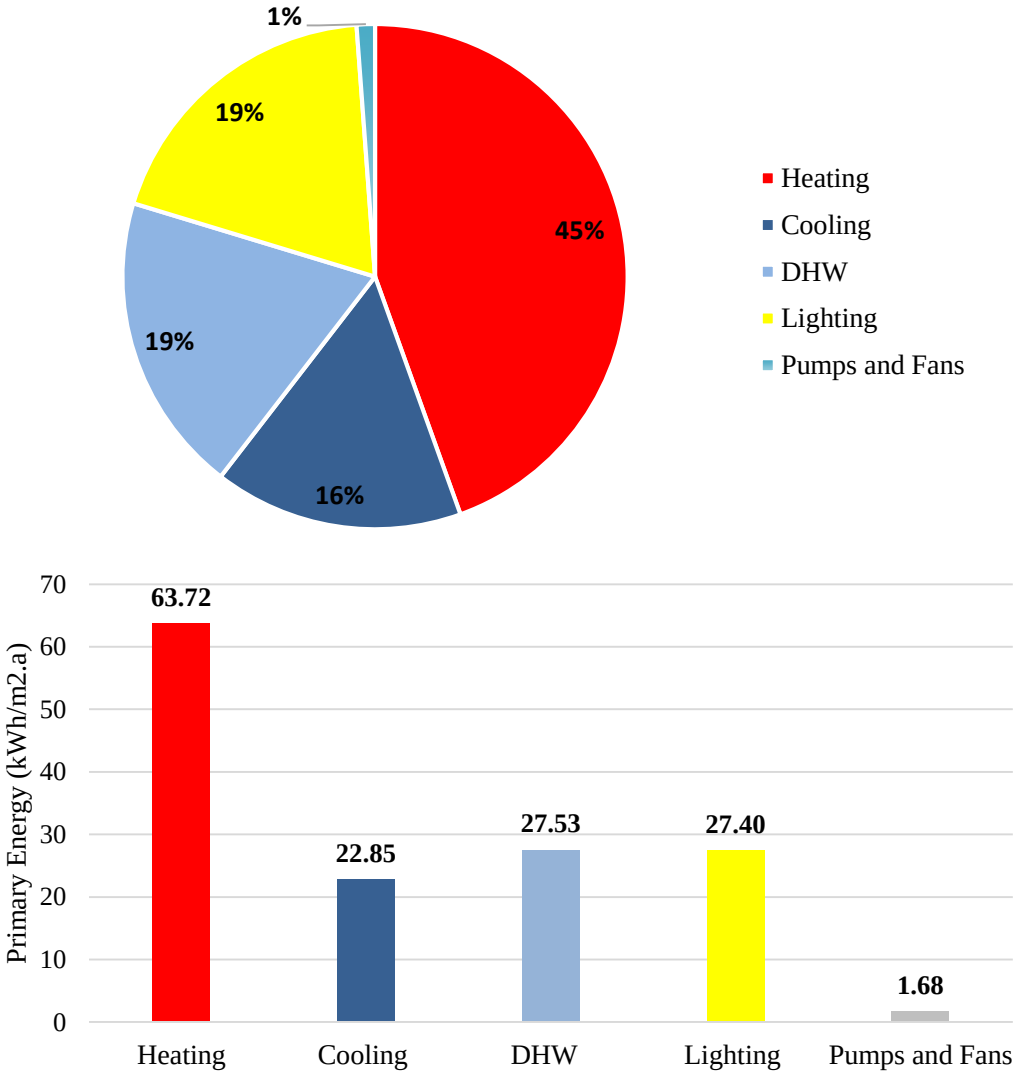

Figure 4.5 : Distribution of yearly PEC of the case study detached building located in Istanbul.

4.3.2 Row Building

Results of energy analyses for the existing row buildings are as followings:

4.3.2.1 Results of energy analyses for the existing row building located in Antalya

Results of the existing building simulations in Antalya climate shows that most of the PEC of the case study reference building belong to cooling. After cooling that consumes 44% of whole 139.25 kWh/m^2.a primary energy, lighting and pumps and fans are located. They are account for 23% and 22% of whole PEC respectively. The heating system is consuming just 4% of total yearly primary energy. Also, DHW are accounts for just 7% of PEC (Figure 4.6).

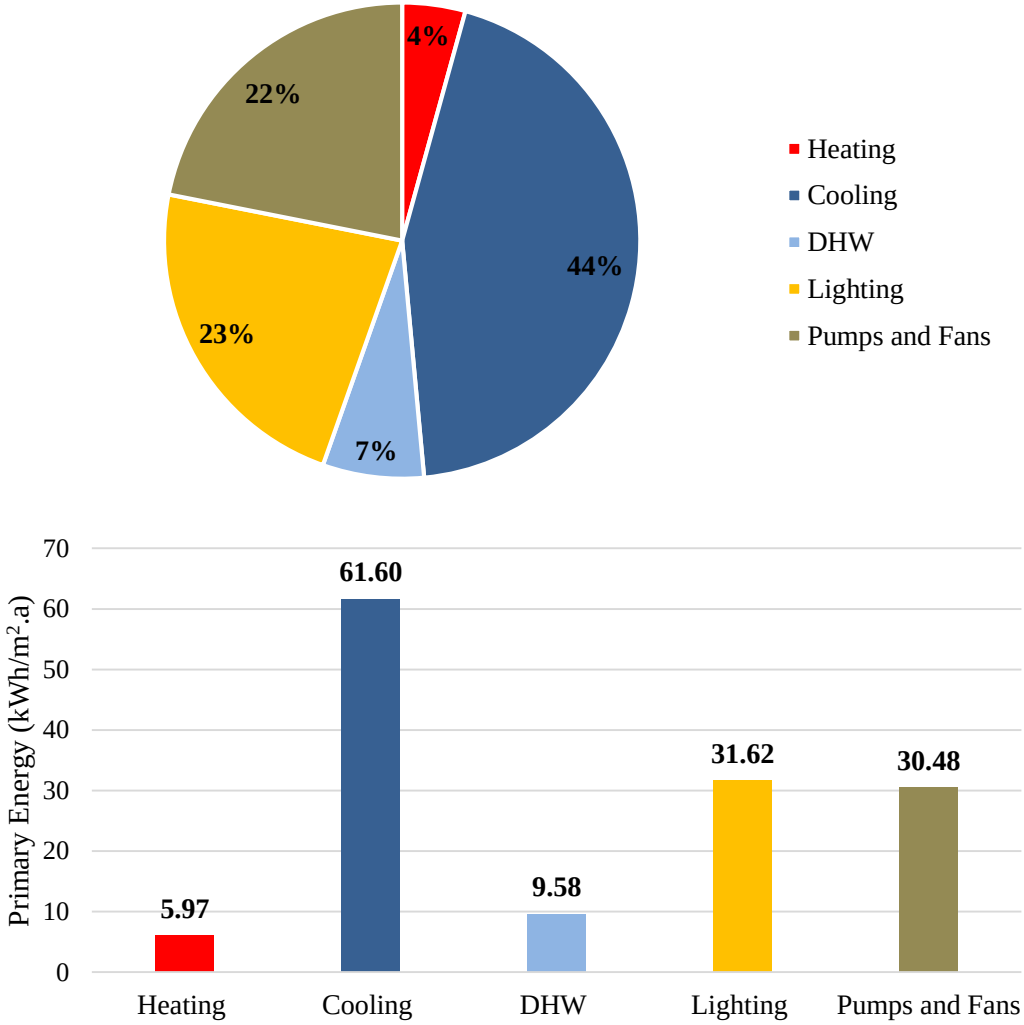

Figure 4.6 : Distribution of yearly PEC in case study row building located in Antalya.

4.3.2.2 Results of energy analyses for the existing row building located in Erzurum

Results of the existing building simulation in Erzurum climate illustrates that most of the Primary Energy Consumption (PEC) of case study reference building belong to heating. After heating that consumes 48% of whole 166.97 kWh/m^2.a PEC, lighting and pumps and fans are located respectively. They totally account for 21% and 18% of whole PEC respectively. The cooling system is consuming just 7% of total yearly primary energy (Figure 4.7).

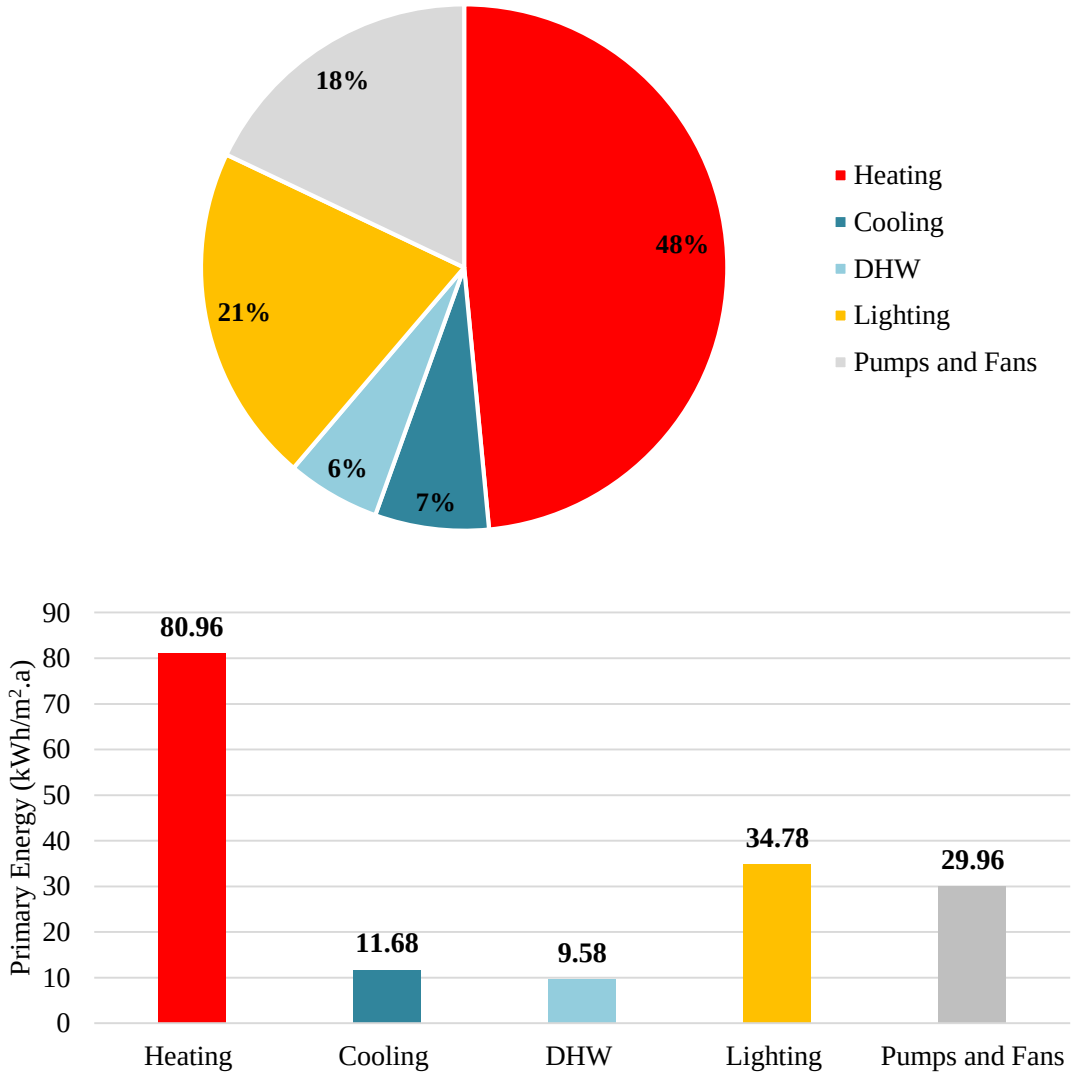

Figure 4.7 : Distribution of yearly PEC of the case study row building located in Erzurum.

4.3.2.3 Results of energy analyses for the existing row building located in Istanbul

Results of the existing building simulation in Istanbul's climate shows that most of the PEC of the existing building belong to heating. After heating that consumes 27% of whole 140.20 kWh/m^2.a PEC, lighting, DHW, and cooling are located. They are account for 23%, 22% and 21% of whole PEC respectively (Figure 4.8) .

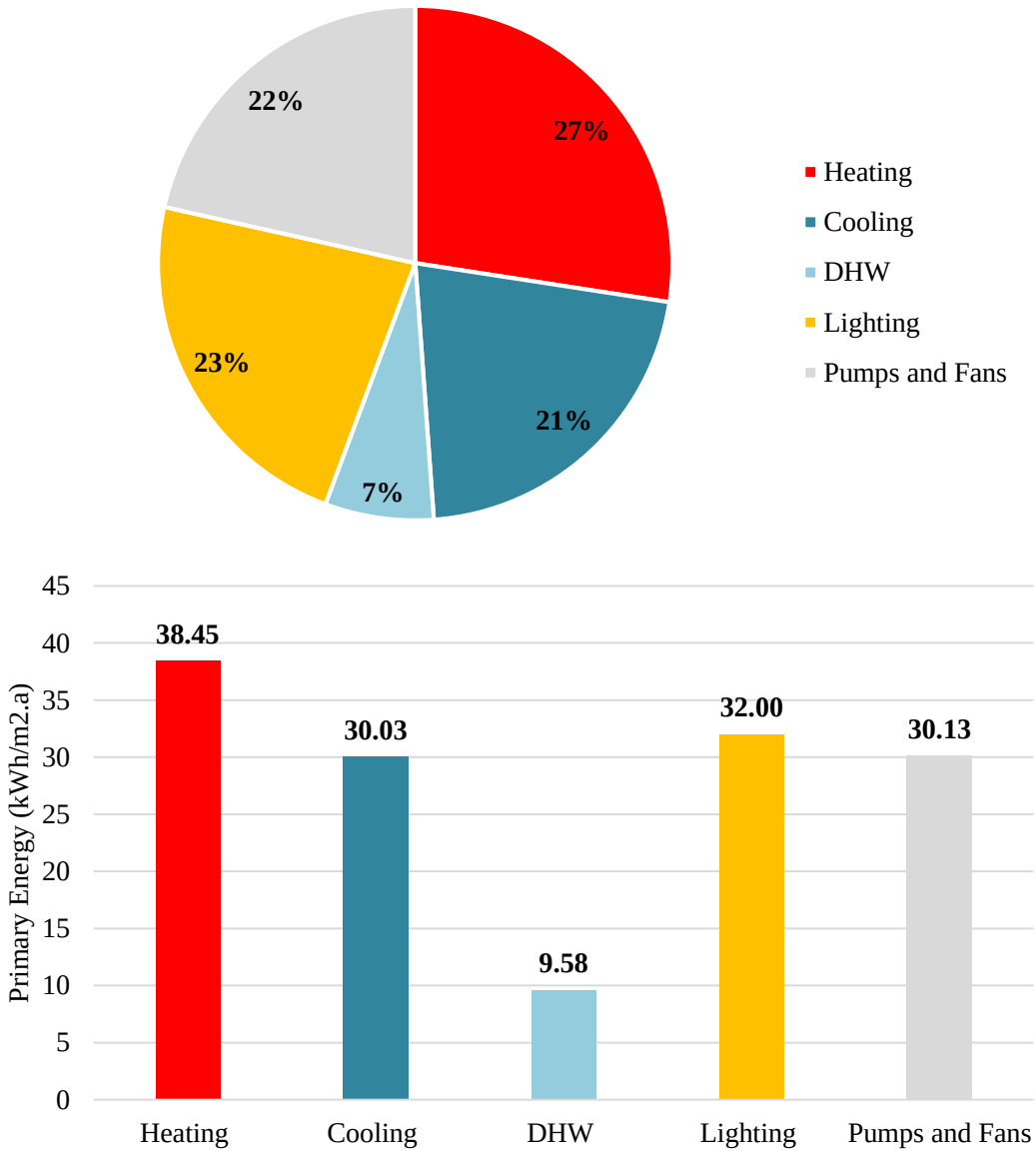

Figure 4.8 : Distribution of yearly PEC of the case study row building located in Istanbul.

4.4 Energy Efficient Retrofit Measures

A series of scenarios were developed to apply to the architectural, mechanical and lighting elements of the buildings to determine applicable and reasonable ones. The

TS825-2013 standard, which is the last version of this mandatory standard for Turkish buildings, provides the basis for architectural measures. Real market analyzes serve as a basis for mechanical and lighting measures. First, the single measures were applied to the buildings and then combinations of measures were developed. Combinations of measures also applied to the case building to define feasible solutions from cost and energy points of view.

Architectural system's retrofit measures include improvement in U-value of building envelope through application/addition of insulation layer, replacement of windows' glass and the addition of shading devices. The improvements in windows' frame are tested during this thesis study as well. Due to the facts that frame improvements are not providing enough energy efficiency, it is eliminated from further analyzes. Roof and ground floor improvements are also analyzed during the study and due to fewer amounts of improvements in the energy performance of buildings, it is preferred to use roof and ground floor improvements together with wall improvements as packages that called opaque systems improvements.

Mechanical systems' measures include modification in heating and cooling systems as well as components. Enhancement in the heating system is applied through replacement of auxiliary components (pumps), the addition of solar collectors to the heating system and replacement of existing boiler with condensing and non-condensing boilers. Heating system's modification includes replacement of radiator system with heated floor system. Cooling system's improvement includes replacement of existing system with High-Efficiency Air Conditioner that has 3.0, 3.5 and 4.0 Coefficient of Performance (COP).

As a renewable energy system, the photovoltaic panels (PV) application is another single measure that is analyzed in this thesis study.

Lighting system's improvement includes replacement of all Compact Floursant Lamps (CFL) with light-emitting diode (LED). Indeed, lighting retrofit is a simple way to make building's energy system more efficient.

Due to the difference in the construction period of the row and detached buildings, their single measures are different. The single measures for detached buildings in the stated three climates are indicated in Table 4.8.

Table 4.8 : Single retrofit measures for the case study detached buildings.

Acr.	Single Measure
S1	The first level of Exterior Wall Insulation based on TS825-2013's required U-value.
S2	The second level of Exterior Wall Insulation, 25% less than TS825-2013's required U-value.
S3	The third level of Exterior Wall Insulation, 50% less than TS825-2013's required U-value.
S4	The first level of Opaque System insulation based on TS825-2013's required U-value.
S5	The second level of Opaque System insulation, 25% less than TS825-2013's required U-value.
S6	The third level of Opaque System insulation, 50% less than TS825-2013's required U-value.
S7	1^{th} Glass Improvement: U= 1.8 W/m²K, T_{vis}= 0.79, SHGC= 0.56 (TS825-2013 requirement)
S8	2^{th} Glass Improvement: U= 1.6 W/m²K, T_{vis}= 0.79, SHGC= 0.56
S9	3^{th} Glass Improvement: U= 1.6 W/m²K, T_{vis}= 0.71, SHGC= 0.44
S10	4^{th} Glass Improvement: U= 1.3 W/m²K, T_{vis}= 0.71, SHGC= 0.44
S11	5^{th} Glass Improvement: U= 1.1 W/m²K, T_{vis}= 0.71, SHGC= 0.44
S12	6^{th} Glass Improvement: U= 0.9 W/m²K, T_{vis}= 0.69, SHGC= 0.48
S13	7^{th} Glass Improvement: U= 0.9 W/m²K, T_{vis}= 0.63, SHGC= 0.39
S14	Shading device (External Blind) construction.
S15	Shading device (Exterior Drop Curtain) construction.
S16	Modification of heating system (Replacement of existing heat pumps by variable flow pumps).
S17	Modification of heating system (Adding solar collectors to the heating system).
S18	Modification the heating components (Replacement of radiator system by heated floor system).
S19	Modification the heating system (Replacement of existing boiler by condensing boiler with 0.93 efficiencies).
S20	Modification the heating system (Replacement of existing boiler by non-condensing boiler with 0.9 efficiencies).
S21	Modification of cooling system (Replacement of current system by High-Efficiency Air Conditioner Units with COP=3.0).
S22	Modification of cooling system (Replacement of current system by High-Efficiency Air Conditioner Units with COP=3.5).
S23	Modification of cooling system (Replacement of current system by High-Efficiency Air Conditioner Units with COP=4.0).
S24	The addition of a photovoltaic system.
S25	All CFL lamps changed to LED lamps.

For row buildings, the situation is a little bit different. As the building is assumed to construct according to TS825-2000, the first level of the wall and whole opaque system improvements are not applicable as the amount of existing building's opaque components' U-value is very close to TS825-2013 requirements. Hence, when any

insulation layer is added to the existing building's opaque system, the related U-value will be very lower than required amount. Thus, just two level of the wall, as well as whole opaque systems improvements, are taken into account. Table 4.9 is illustrating the single measures for row buildings in the stated three climates.

Table 4.9 : Single retrofit measures for the case study row buildings.

Acr.	Single Measure
S1	The second level of Exterior Wall Insulation, 25% less than TS825-2013's required U-value.
S2	The third level of Exterior Wall Insulation, 50% less than TS825-2013's required U-value.
S3	The second level of Opaque System insulation, 25% less than TS825-2013's required U-value.
S4	The third level of Opaque System insulation, 50% less than TS825-2013's required U-value.
S5	1th Glass Improvement: U= 1.8 W/m²K, T_{vis}= 0.79, SHGC= 0.56 (TS825-2013 requirement)
S6	2th Glass Improvement: U= 1.6 W/m²K, T_{vis}= 0.79, SHGC= 0.56
S7	3th Glass Improvement: U= 1.6 W/m²K, T_{vis}= 0.71, SHGC= 0.44
S8	4th Glass Improvement: U= 1.3 W/m²K, T_{vis}= 0.71, SHGC= 0.44
S9	5th Glass Improvement: U= 1.1 W/m²K, T_{vis}= 0.71, SHGC= 0.44
S10	6th Glass Improvement: U= 0.9 W/m²K, T_{vis}= 0.69, SHGC= 0.48
S11	7th Glass Improvement: U= 0.9 W/m²K, T_{vis}= 0.63, SHGC= 0.39
S12	Shading device (External Blind) construction.
S13	Shading device (Exterior Drop Curtain) construction.
S14	Modification of heating system (Replacement of current heat pumps by variable flow pumps)
S15	Modification of heating system (Adding solar collectors to the heating system).
S16	Modification the heating components (Replacement of radiator system by heated floor system).
S17	Modification the heating system (Replacement of existing combi-boilers by condensing combi-boilers with 0.93 efficiencies).
S18	Modification the heating system (Replacement of existing combi-boilers by central condensing boiler with 0.93 efficiencies).
S19	Modification the heating system (Replacement of existing combi-boilers by central non-condensing boiler with 0.9 efficiencies).
S20	Modification of cooling system (Replacement of current system by High-Efficiency Air Conditioner Units with COP=3.5).
S21	Modification of cooling system (Replacement of current system by High-Efficiency Air Conditioner Units with COP=4.0).
S22	The addition of a photovoltaic system.
S23	All CFL lamps changed to LED lights.

The numerical values of individual measures are indicated in Table 4.10.

Table 4.10 : Numerical values for single retrofit measures.

	Building Component	U-Value (W/m²K)		
		Istanbul	**Antalya**	**Erzurum**
First level of Wall improvement (TS825-2013 requirements)	Wall	0.57	0.66	0.36
Second level of Wall improvement	Wall	0.43	0.50	0.27
Third level of Wall improvement	Wall	0.29	0.33	0.18
First level of Opaque system's improvement (TS825-2013 requirements)	Wall	0.57	0.66	0.36
	Roof	0.38	0.43	0.21
	Ground Floor	0.57	0.66	0.36
Second level of Opaque system's improvement	Wall	0.43	0.50	0.27
	Roof	0.28	0.32	0.15
	Ground Floor	0.43	0.50	0.27
The third level of Opaque system's improvement	Wall	0.29	0.33	0.18
	Roof	0.19	0.21	0.10
	Ground Floor	0.29	0.33	0.18

From cost and energy calculation points of view, it is necessary to provide proper application detail to increase the accuracy of calculations. Amounts and definition of work should be providing thoroughly. For exterior wall improvements, as the aim of this thesis study is to reduce the initial investment cost in such a way that owners can involve in the projects as a financier, any interference in existing situation of walls is prohibited. Thus, just insulation system is added to the exterior side of the wall without any destruction. Detail of existing walls differs due to different U-value of existing walls. For example, for all buildings located in Erzurum, there is insulation layer in the wall systems while just row building located in Antalya have insulation layer in its wall system. Figure 4.9 is indicating the detail of insulation application on exterior wall system.

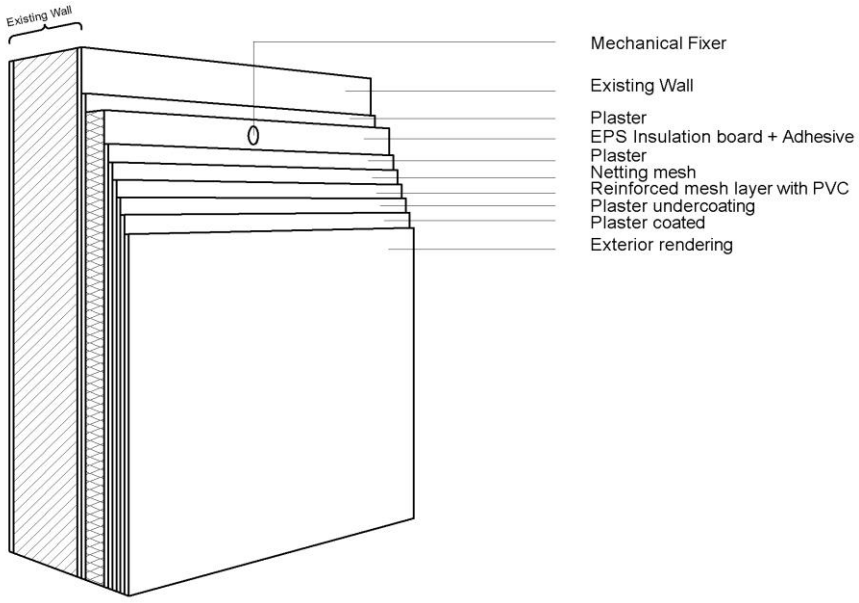

Figure 4.9 : Architectural detail of insulation application on the exterior walls.

Based on Figure 4.9, the amount of each material per m^2 of the exterior wall is illustrated in Table 4.11. Real market analyzes are performed to define these quantities. Quantity indicated in different construction companies' catalogs are taken into account (Table 4.11).

Table 4.11 : The amount of additional materials per $1m^2$ of the wall for insulation application.

Explanation	Quantity
EPS Insulation board	1 m^2
Adhesive	4.5-5 kg
Plaster	4.5-5 kg
Mechanical Fixer	6 piece
Netting Mesh	1.1 m^2
Reinforced Mesh Layer with PVC	0.25 m
Plaster Undercoating	0.2 kg
Plaster Coated	2.5 kg
Exterior Rendering	0.36 kg

Improvements of flat roofs are proposed to be according to Figure 4.10. A layer of geotextile felt between insulation board and cement tile together with four mechanical fixers per m^2 are included in the analyses. Similar to wall systems, details of existing roofs differ due to different U-value required by TS-825 standards belong to construction period. Also, any interference in the current situation of roofs is

prohibited to prevent from any extra cost. Thus, just insulation system is added to the exterior side of roofs without any destruction (Figure 4.10).

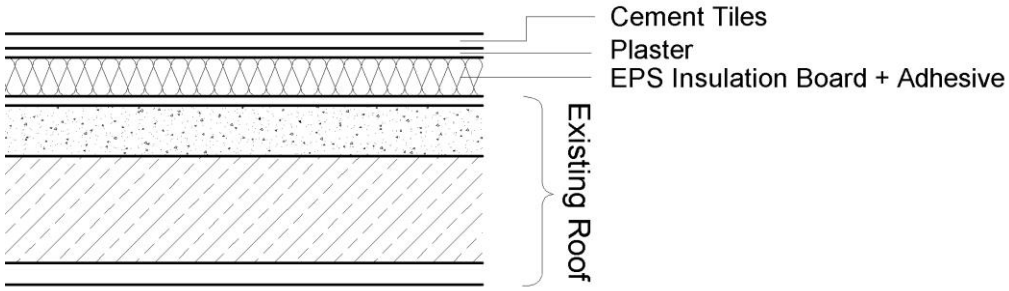

Figure 4.10 : Architectural detail of insulation application on the row buildings' flat roofs.

Based on Figure 4.10, the amount of each material per m^2 of row buildings' flat roof is illustrated in Table 4.12. Real market analyzes are performed to define these quantities. Quantity indicated in different construction companies' catalogs are taken into account (Table 4.12).

Table 4.12 : The amount of additional materials per insulation of $1m^2$ of a flat roof.

Explanation	Quantity
EPS Insulation board	1 m^2
Adhesive	4.5-5 kg
Plaster	4.5-5 kg
Cement Tile	1 m^2

For sloped roofs that are existing in detached buildings, detail indicated in Figure 4.11 is applied. As the roof is unoccupied, just a layer of heat insulation together with an adhesive layer are bedded on the outer level of the last floor's ceiling (Figure 4.11).

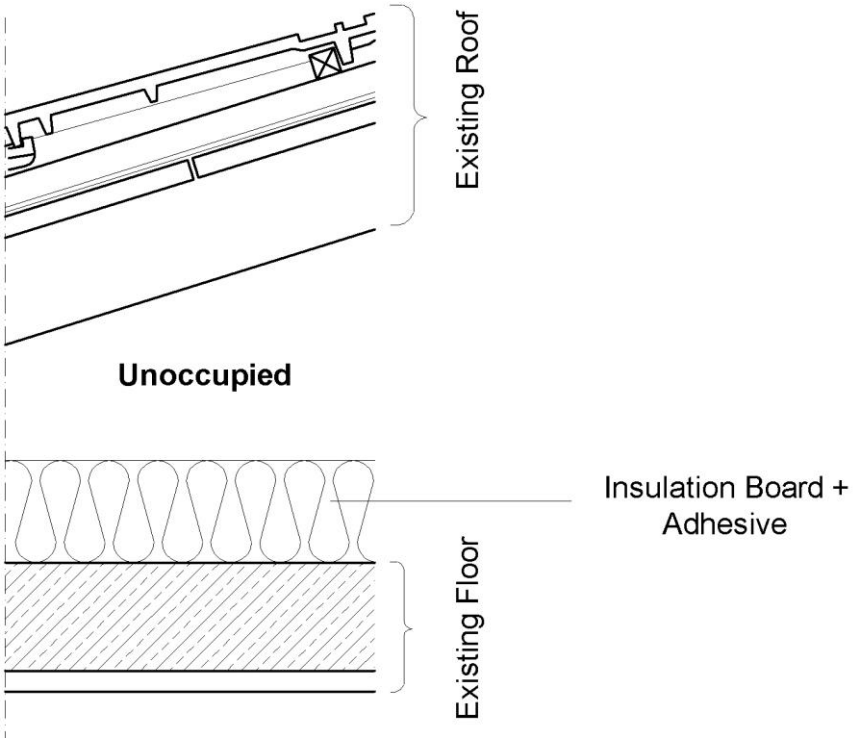

Figure 4.11 : Architectural detail of insulation application on the row buildings' sloped roofs.

The amount of additional materials for insulation application in the sloped roof of detached buildings are indicated in Table 4.13. Purposed cost analyses are done based on these quantities (Table 4.13).

Table 4.13 : The amount of additional materials per $1m^2$ of the sloped roof for insulation application.

Explanation	Quantity
EPS Insulation board	1 m^2
Adhesive	4.5-5 kg

For ground floor insulation, as there is an underground floor that is using as mechanical room and unoccupied, the insulation layer is located at the bottom of the floor to prevent any disturbance for the occupant during the application process. The detail indicated in Figure 4.12 is used in the related analyzes. To prevent thermal bridge problems, 40cm of insulation layers are added to the conjunctions of the ceiling with walls. Mechanical fixers prevent from any material fall. Together with insulation board and mechanical fixers, a layer of gypsum plastering is included in the analyses (Figure 4.12).

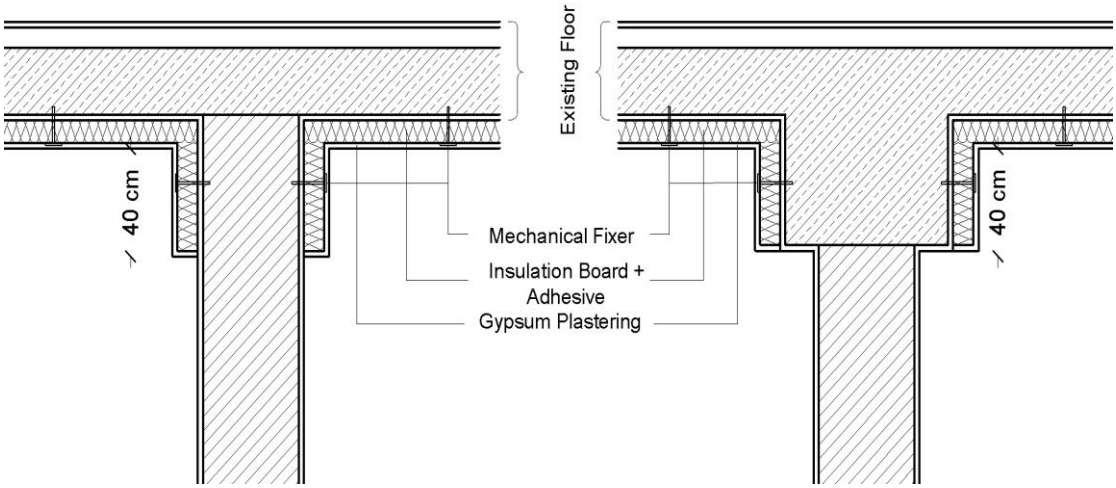

Figure 4.12 : Architectural detail of insulation application on the ground floors.

The amount of additional materials for ground floor insulation is indicated in Table 4.14. Purposed cost analyzes are done based on these quantities (Table 4.14).

Table 4.14 : The amount of additional materials per $1m^2$ of the ground floor for insulation application.

Explanation	Quantity
EPS Insulation board	1 m^2
Adhesive	4.5-5 kg
Mechanical Fixer	6 piece
Gypsum Plaster	4.5-5 kg

4.5 Energy-Cost Analyses for the Retrofit Measures

In this section, the results of analyses for the detached and row buildings based on the related methodology indicated in section 3.4 would be presented. The retrofit measures determined in section 3.3 for each building category are applied to the existing buildings models located in each representative city, and the results are presented in the followings:

4.5.1 Detached Building

Results of energy and cost analyses for the detached buildings located in Antalya, Erzurum and Istanbul are as followings:

4.5.1.1 Results of energy-cost analyses for the detached building located in Antalya

Based on Table 4.8, a set of retrofit measures were created to apply to the case study building in Antalya. Table 4.15 is presenting the amount of insulation layers and glazing system types that had been implemented to the case study building as the single retrofit measures (Table 4.15). For the buildings' energy systems, the descriptions identified in Table 4.8 were used.

Table 4.15 : Description of single retrofit measures of architectural components for detached building in Antalya.

Acr.	Values	Description
S1	U_{wall}= 0.66 W/m^{2}K	3cm Insulation Layer 0.035W/mK
S2	U_{wall}= 0.50 W/m^{2}K	5cm Insulation 0.035W/mK
S3	U_{wall}= 0.36 W/m^{2}K	8cm Insulation 0.035W/mK
S4	U_{wall}= 0.66 W/m^{2}K	3cm Insulation Layer 0.03W/mK
	U_{roof}= 0.43 W/m^{2}K	4cm Insulation Layer 0.035W/mK
	U_{floor}= 0.66 W/m^{2}K	3cm Insulation Layer 0.03W/mK
S5	U_{wall}= 0.50 W/m^{2}K	5cm Insulation Layer 0.035W/mK
	U_{roof}= 0.31 W/m^{2}K	8cm Insulation Layer 0.035W/mK
	U_{floor}= 0.50 W/m^{2}K	5cm Insulation Layer 0.035W/mK
S6	U_{wall}= 0.36 W/m^{2}K	8cm Insulation Layer 0.035W/mK
	U_{roof}= 0.21 W/m^{2}K	12cm Insulation Layer 0.035W/mK
	U_{floor}= 0.36 W/m^{2}K	8cm Insulation Layer 0.035W/mK
S7	U= 1.8 W/m^2.K, T_{vis}= 0.79, SHGC= 0.56	Isıcam Sinerji (4+9+4 with air)
S8	U= 1.6 W/m^2.K, T_{vis}= 0.79, SHGC= 0.56	Isıcam Sinerji (4+12+4 with air)
S9	U= 1.6 W/m^2.K, T_{vis}= 0.71, SHGC= 0.44	Isıcam Konfor (4+12+4 with air)
S10	U= 1.3 W/m^2.K, T_{vis}= 0.71, SHGC= 0.44	Isıcam Konfor (4+16+4 with air)
S11	U= 1.1 W/m^2.K, T_{vis}= 0.71, SHGC= 0.45	Isıcam Konfor (4+16+4 with argon)
S12	U= 0.9 W/m^2.K, T_{vis}= 0.69, SHGC= 0.48	Isıcam Sinerji3+ (4+12+4+12+4 air, Low-E + clear glass + Low-E)
S13	U= 0.9 W/m^2.K, T_{vis}= 0.63, SHGC= 0.39	Isıcam Konfor3+ (4+12+4+12+4 air, Solar Low-E + clear glass + Low-E)

First of all, the energy analyses had been done for single retrofit measures, then based on that analyzes, further studies have been done for combined measures. The energy consumption of each single retrofit measure is calculated and indicated in Figure 4.13. The results show that PV system application (S24) is more efficient than other actions. It can reduce the PEC by approximately 21%. The opaque system retrofits (S4-S6) are more effective than other architectural improvements (S1-S15) while wall retrofits

solely (S1-S3) act similarly to opaque system retrofit. Opaque system's improvement can reduce the amount of PEC by more than 15% solely. Cooling system amendments (S21-S23) is effective as much as opaque system enhancements. Glazing system retrofits (S7-S13) are not useful solely, it can decrease about 9.5% of PEC at most. Shading device application (S14 and S15) can improve PEC by 5.5% mostly. The reason is that, however, shading device applications are reducing the amount of cooling energy consumption, they increase the amount of lighting energy consumption at the same time. Among improvement scenarios for heating system (S16-S20), solar collector application (S17) by just 7% is the most practical scenarios from PEC point of view while replacement of current boiler with condensing boiler (S19) can reduce PEC by just 5% and reach to 147.1 kWh/m^2.a. Lighting system improvement (S25) reduces the PEC by less than 4%. Opaque system improvements can reduce the heating system's PEC by about 85% while decreasing the cooling system's PEC by at most 1.5% (Figure 4.13).

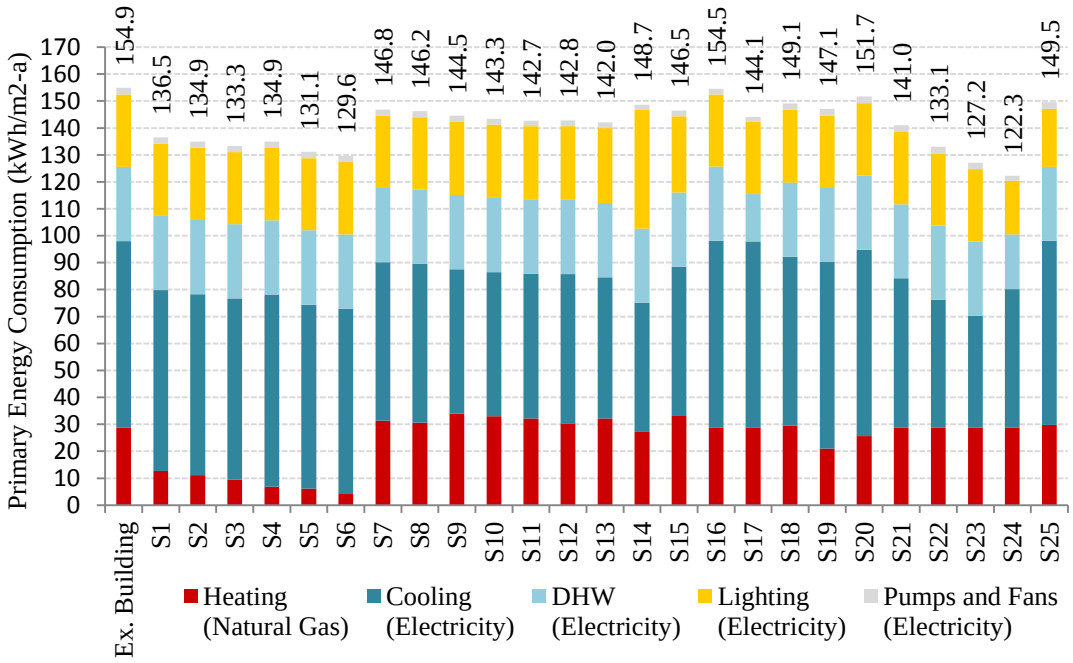

Figure 4.13 : Yearly PEC of each single measure of detached building in Antalya.

The initial investment cost for each single action is illustrated in Table 4.16. When available, costs from three material producer are provided as unit price for each measure. In roof and floor retrofits, the cost of extra materials is added to unit costs as a constant value (Table 4.16). The related cost of combined measures is calculated based on this table as well.

Table 4.16 : Cost calculations for the improvement of the detached building located in Antalya.

Acr.	Improved Component	Amount (m^2 / piece)	Average unit Cost (TL)	Material Cost (TL)	Indirect Cost (TL)	TAX (TL)	Total Cost (TL)
S1	Wall	1191.53	24.11	28730.57	7182.64	6464.38	42377.59
S2	Wall	1191.53	28.70	34195.72	8548.93	7694.04	50438.69
S3	Wall	1191.53	35.91	42784.27	10696.07	9626.46	63106.79
S4	Wall	1191.53	13.39	36853.67	9213.42	8292.08	54359.17
	Roof	385.00	8.26				
	GF	357.00	12.44				
S5	Wall	1191.53	8.31	42132.84	10533.21	9479.89	62145.95
	Roof	385.00	13.33				
	GF	357.00	25.60				
S6	Wall	1191.53	24.11	56710.94	14177.74	12759.96	83648.64
	Roof	385.00	13.39				
	GF	357.00	8.31				
S7	Glass	336.00	46.78	15716.40	3929.10	3536.19	23181.69
S8	Glass	336.00	47.43	15934.80	3983.70	3585.33	23503.83
S9	Glass	336.00	53.70	18043.20	4510.80	4059.72	26613.72
S10	Glass	336.00	60.15	20210.40	5052.60	4547.34	29810.34
S11	Glass	336.00	60.90	20462.40	5115.60	4604.04	30182.04
S12	Glass	336.00	83.00	27888.00	6972.00	6274.80	41134.80
S13	Glass	336.00	89.30	30004.80	7501.20	6751.08	44257.08
S14	SD	1	73517.30	73517.30	18379.33	20172.43	112069.06
S15	SD	1	74367.57	74367.57	18591.89	20405.73	113365.19
S16	VHP	15	320.00	4800.00	1200.00	1080.00	7080.00
S17	SC	15	2364.77	35471.55	8867.88	7981.10	52320.53
S18	HF	15	4566.75	68501.28	17125.32	15412.79	101039.39
S19	Con. Boiler	1	4000.00	4000.00	1000.00	900.00	5900.00
S20	non-Con. Boiler	1	3380.00	3380.00	845.00	760.50	4985.50
S21	AC COP3.0	15	2663.55	39953.29	9988.32	8989.49	58931.10

Table 4.16 (continued): Cost calculations for the improvement of the detached building located in Antalya.

Acr.	Improved Component	Amount (m^2 / piece)	Average unit Cost (TL)	Material Cost (TL)	Indirect Cost (TL)	TAX (TL)	Total Cost (TL)
S22	AC COP3.5	15	2446.60	36699.05	9174.76	8257.29	54131.10
S23	AC COP4.0	15	3348.30	50224.47	12556.12	11300.51	74081.10
S24	PV	42	1220.27	51251.20	12812.80	11531.52	75595.52
S25	LED	300	14.00	4194.92	1048.73	943.86	6187.50

Cost per housing unit in Figure 4.14 indicates the amount of money that each flat owner should pay for the actions. The third level of opaque system amendment (S6) requires a huge budget for each owner. Shading device applications (S14-S15) together with heated floor application (S18), PV application (S24) and replacement of current air conditioner with High-Efficiency ones with COP=4.0 (S23) also provide owners with a very high payment for actions. From these measures, just PV application and opaque system improvement can be considered to use in step-by-step retrofit as it can be divided into some steps. Replacement of existing boiler with condensing and non-condensing boiler (S19-S20), modification of existing heating system by adding the variable heat pump (S16) and replacement of existing lamps with LED lights (S25) are the most cheaper measures. Other measures seem to have the reasonable amount of payment while items with more than 2270TL cost need to pay more attention (Figure 4.14).

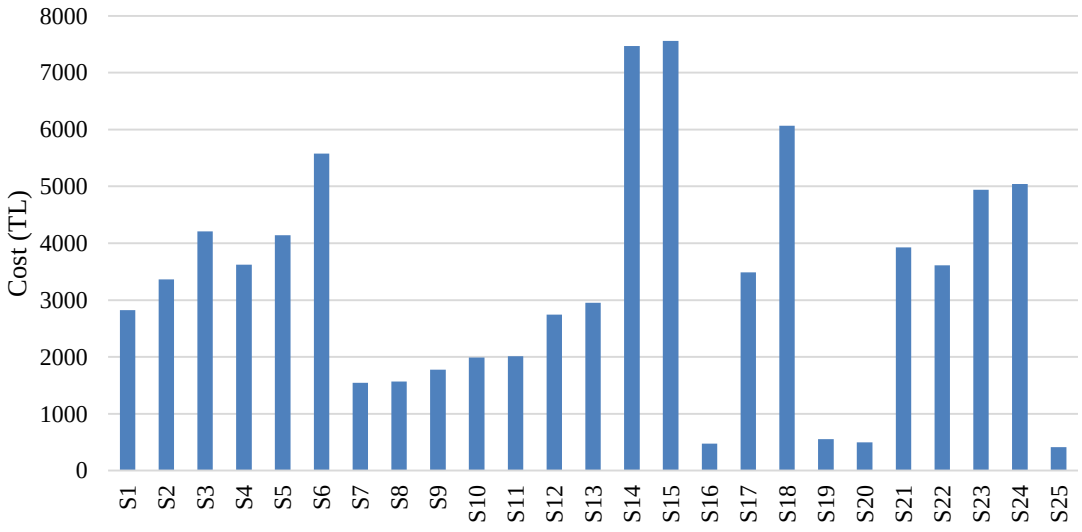

Figure 4.14 : Cost per flat for single retrofit measures (Detached-Antalya).

The payback period for each single measure is calculated to determine its feasibility. Replacement of the existing lamps with LED ones (S25) by less than a four-year period is at the first rank while the replacement of existing boiler with condensing boiler (S19) is located in the second position. Some of the glazing system improvements (S9-S11) and PV application (S24) are located in the third rank simultaneously while replacement of current air conditioner with High-Efficiency ones with COP=3.5 (S22) is following them. From architectural improvements (S1-S15) most of the glass enhancements (S7-S11) has less than 10-year payback period while most of the measures have less than 15-year payback period (Figure 4.15).

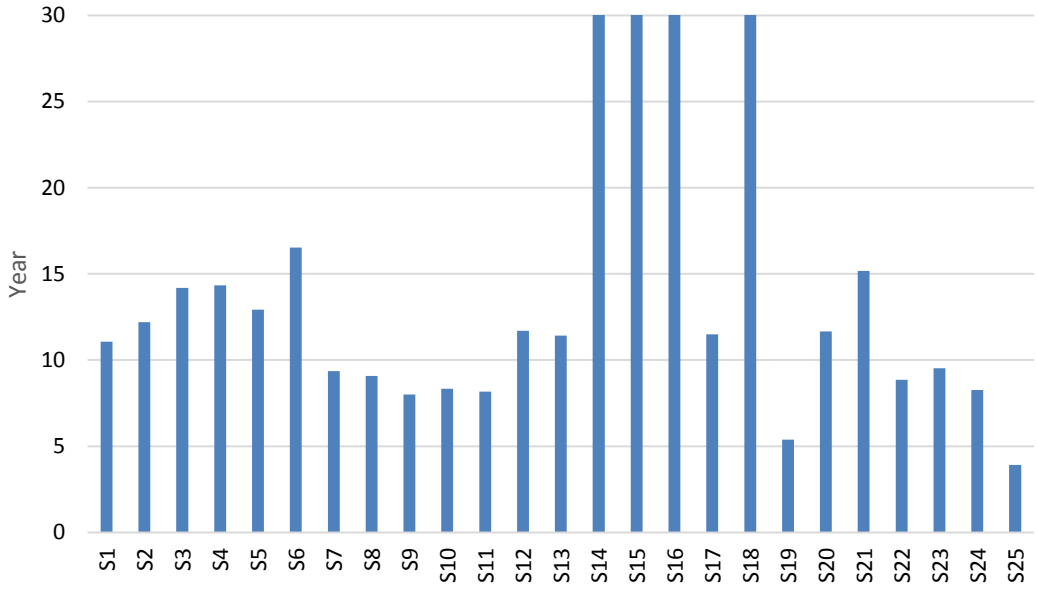

Figure 4.15 : The payback period of each single measure (Detached-Antalya).

Figure 4.16 shows the amount of CO_2 emission of each single measure. It is possible to reach to about 22% of CO_2 emission saving by application of S24 that is PV system application. Replacement of current air conditioner with High-Efficiency ones with COP=4.0 (S23) will lead to about 18% CO_2 emission saving. About 9 actions can provide more than 10% CO_2 emission saving (Figure 4.16).

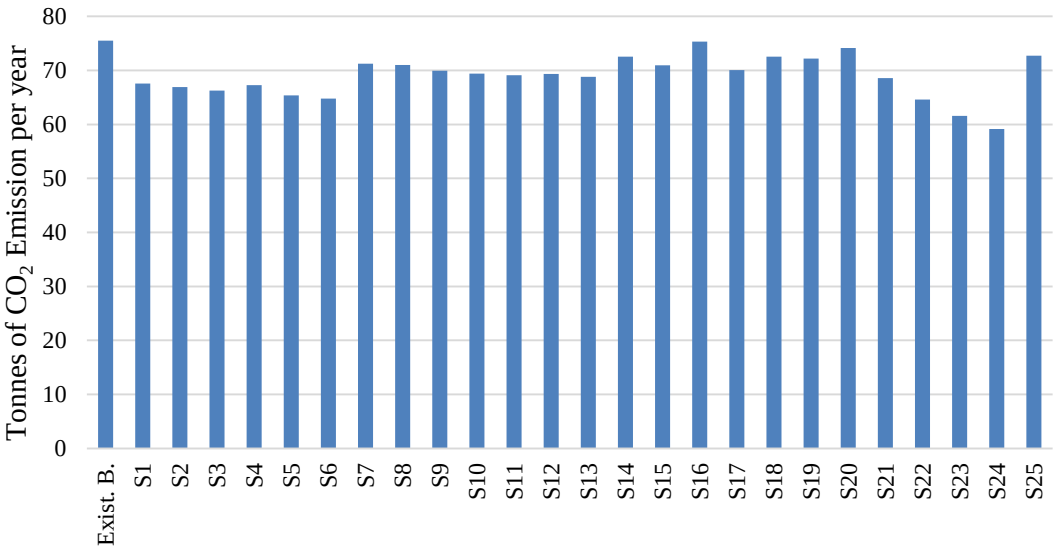

Figure 4.16 : CO_2 Emission of each single measure (Detached-Antalya).

The existing case study building has approximately 562 TL/m^2 global cost. Replacement of the existing boiler with condensing boiler (S19) with 513 TL/m^2 global cost and 122 kWh/m^2 PEC is located at the lowest point of the graph. Four measures are located above case study building, hence, should be eliminated from further analyzes. Thus, shading system applications (S14-S15) together with the application of heated floor (S18), replacement of existing heat pump with variable heat pump (S16) had been excluded from analyzes. The third level of the wall and opaque system amendments (S3 and S6) are located above the second level of related amendments, thus, are irrational to include in combined measures. From glazing system improvements, first to the fifth level of the amendment (S7-S11) are decreasing the amount of global cost and PEC of existing case study building. Sixth and seventh level of glass improvements (S12-S13) have more global cost in comparison with S11, hence, will not lead to reaching the lowest point of the whole measures global cost vs. primary energy consumption graph and should be eliminated from further analyzes. Replacement of existing boiler with a non-condensing boiler with 0.9 efficiencies (S20) and adding solar collectors to the heating system (S17) are not reducing the global cost by a considerable amount and eliminated from further analyzes. Thus, the number of required simulations is reduced significantly (Figure 4.17).

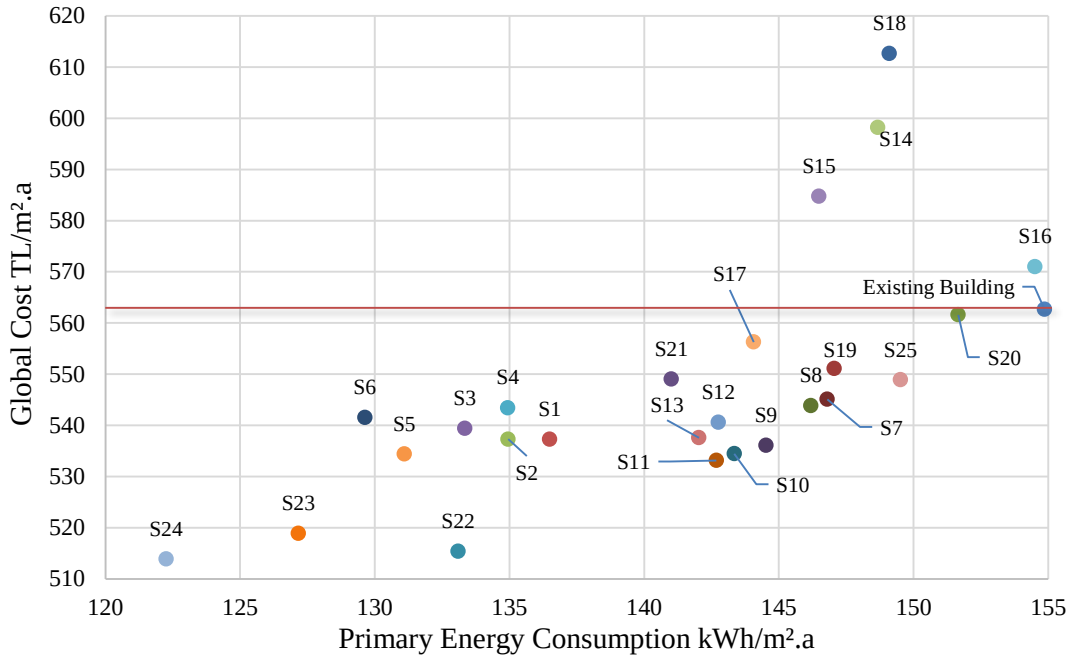

Figure 4.17 : The global cost vs. primary energy consumption graph for single measures (Detached-Antalya).

Rest of the single measures combined to define the retrofit packages. To reduce the number of simulations, first of all, architectural and mechanical system's retrofit measures' combination are established, applied to the existing building and then simulated. After the conclusion of the energy-cost analyses for the related combined measures, the results have been transferred to the global cost-primary energy graph. The lowest points of the graph are indicating the economically reasonable combined measures except lighting and renewable measures (ERCMs). From architectural and mechanical combination measures, nine scenarios are ERCMs. The characteristics of these scenarios are indicated in Table 4.17. In general, when the second level of opaque system improvements together with the third, fourth and fifth level of glazing system amendments combined with the second level of cooling system enhancement with or without boiler improvements, the retrofit will be located at the optimum area. Moreover, ERCMs can reduce global cost by approximately 20% and PEC by about 37% (Figure 4.18, Table 4.17).

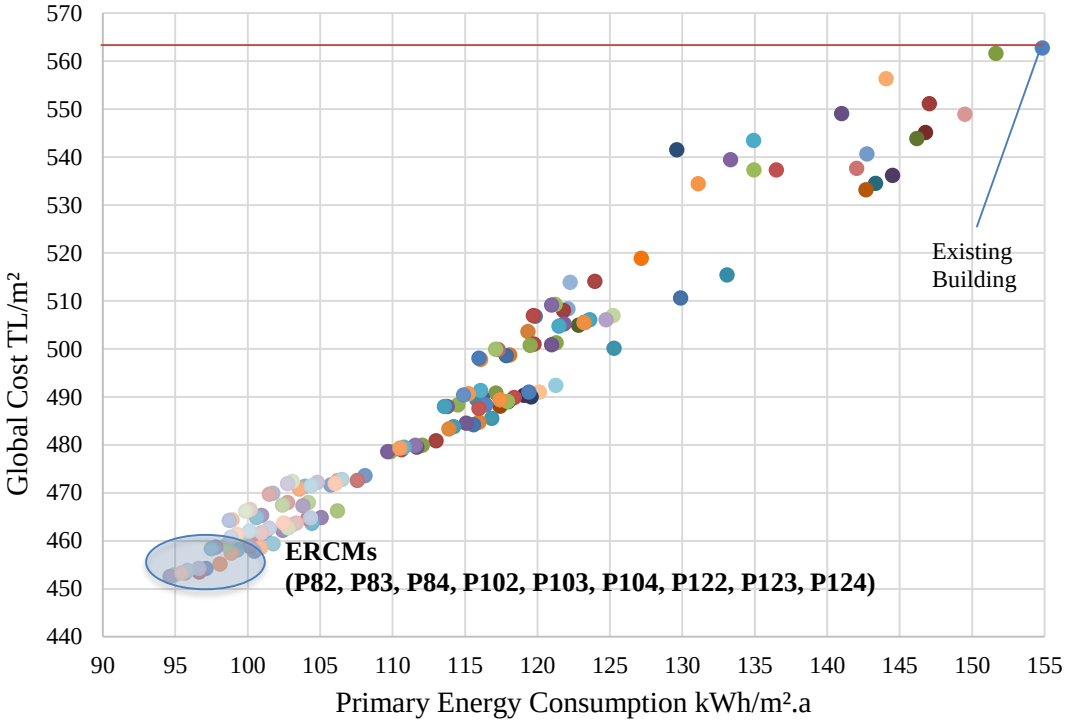

Figure 4.18 : The global cost vs. primary energy consumption graph for the combination of the architectural and mechanical measures (Detached-Antalya).

Table 4.17 : Energy efficiency measures that constitute the ERCMs (Detached-Antalya).

Acr.	Energy Efficiency Measure (Architecture)	Energy Efficiency Measure (HVAC System)
P82	U_{Opaque} 25% + 3th Glazing (S5+S9)	Cooling Coil COP = 3.5 (S22)
P83	U_{Opaque} 25% + 4th Glazing (S5+S10)	Cooling Coil COP = 3.5 (S22)
P84	U_{Opaque} 25% + 5th Glazing (S5+S11)	Cooling Coil COP = 3.5 (S22)
P102	U_{Opaque} 25% + 3th Glazing (S5+S9)	Condensing Boiler + Coil COP = 3.5 (S22+S19)
P103	U_{Opaque} 25% + 4th Glazing (S5+S10)	Condensing Boiler + Coil COP = 3.5 (S22+S19)
P104	U_{Opaque} 25% + 5th Glazing (S5+S11)	Condensing Boiler + Coil COP = 3.5 (S22+S19)
P122	U_{Opaque} 25% + 3th Glazing (S5+S9)	Non-Condensing Boiler + Coil COP = 3.5 (S22+S18)
P123	U_{Opaque} 25% + 4th Glazing (S5+S10)	Non-Condensing Boiler + Coil COP = 3.5 (S22+S18)
P124	U_{Opaque} 25% + 5th Glazing (S5+S11)	Non-Condensing Boiler + Coil COP = 3.5 (S22+S18)

Then, lighting system improvements and after that PV applications are applied to the ERCMs (ERCMs+LED application and ERCMs+LED+PV application). Similar analyzes are done for related combined measures, and the necessary global cost vs.

primary energy consumption graph is provided for these actions. By application of lighting system amendment and PV system to the ERCMs, it is possible to reach to about 400 TL/m^2 global cost and approximately 60 kWh/m^2 PEC. As these combinations are located at the lowest point of the global cost vs. primary energy consumption graph, they are cost-optimal actions for this building. So, the cost-optimal actions can provide more than 62% primary energy saving together with 30% global cost saving for the case study building located in Antalya (Figure 4.19).

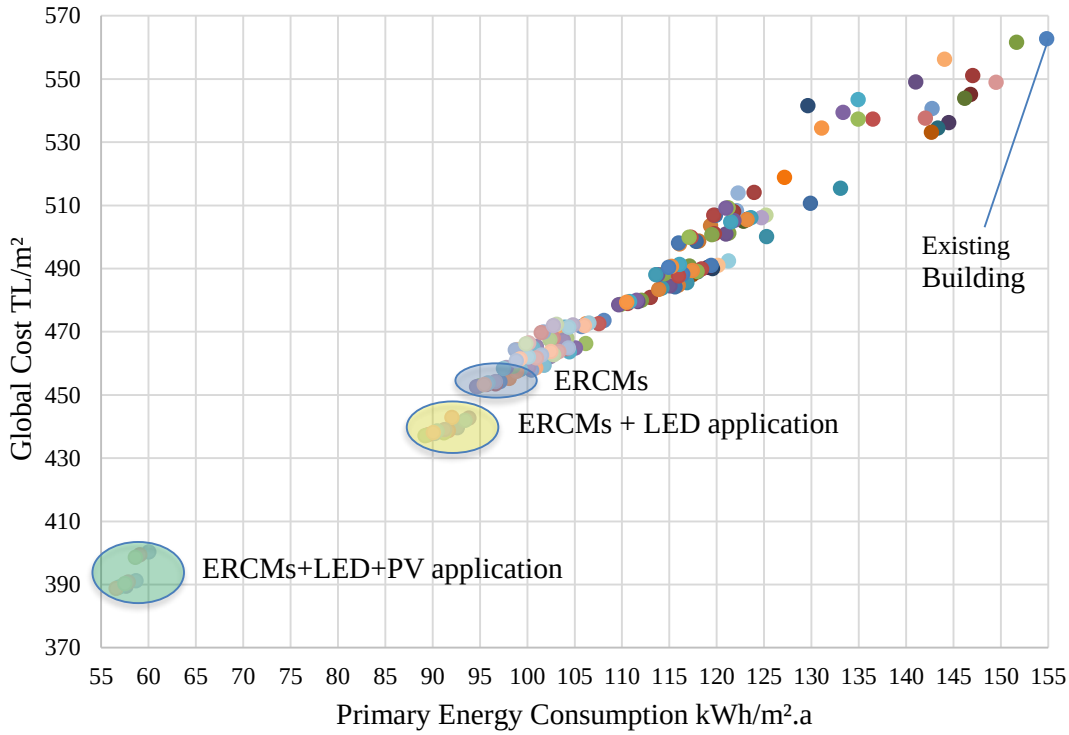

Figure 4.19 : The global cost vs. primary energy consumption graph for whole single and combined scenarios (Detached-Antalya).

The initial investment cost and cost per flat of optimum cases are indicated in Table 4.18. As seen there, the contribution amount for each owner in all cases is more than the reasonable amount. Thus, all of them should be analyzed to apply as step-by-step retrofits. All scenarios have about/less than nine years' payback period (Table 4.18).

Table 4.18 : Cost per flat and payback time for optimum scenarios (Detached-Antalya).

	Total Initial Investment Cost (TL)	Cost per Flat (TL)	Payback Period (yr.)
P82+LED+PV	224673.79	14978.25	9.00
P83+LED+PV	227870.41	15191.36	9.06
P84+LED+PV	228242.11	15216.14	9.04

Table 4.18 (continued): Cost per flat and payback time for optimum scenarios (Detached-Antalya).

	Total Initial Investment Cost (TL)	Cost per Flat (TL)	Payback Period (yr.)
P102+LED+PV	214390.09	14292.67	8.42
P103+LED+PV	217586.71	14505.78	8.50
P104+LED+PV	217958.41	14530.56	8.50
P122+LED+PV	214390.09	14292.67	8.48
P123+LED+PV	217586.71	14505.78	8.56
P124+LED+PV	217958.41	14530.56	8.55

4.5.1.2 Results of energy-cost analyses for the detached building located in Erzurum

Based on Table 4.8, a set of retrofit measures were created to apply to the case study building in Erzurum. Table 4.19 is representing the amount of insulation layers, and that were applied to the case study building as the single retrofit measures (Table 4.19). For the glazing system, the descriptions available in Table 4.15 and for energy systems, the descriptions identified in Table 4.8 were used.

Table 4.19 : Description of single retrofit measures of architectural components for detached building in Erzurum.

Acr.	Values	Description
S1	U_{wall} = 0.36 W/m^2.K	6cm Insulation Layer- 0.03W/m.K
S2	U_{wall} = 0.27 W/m^2.K	8cm Insulation Layer- 0.03W/m.K
S3	U_{wall} = 0.18 W/m^2.K	12cm Insulation Layer- 0.03W/m.K
S4	U_{wall} = 0.36 W/m^2.K	6cm Insulation Layer- 0.03W/m.K
	U_{roof} = 0.21 W/m^2.K	10cm Insulation Layer- 0.035W/m.K
	U_{floor} = 0.36 W/m^2.K	5cm Insulation Layer- 0.03W/m.K
S5	U_{wall} = 0.27 W/m^2.K	8cm Insulation Layer- 0.03W/m.K
	U_{roof} = 0.16 W/m^2.K	14cm Insulation Layer- 0.035W/m.K
	U_{floor} = 0.27 W/m^2.K	8cm Insulation Layer- 0.035W/m.K
S6	U_{wall} = 0.18 W/m^2.K	12cm Insulation Layer- 0.03W/m.K
	U_{roof} = 0.11 W/m^2.K	18cm Insulation Layer- 0.035W/m.K
	U_{floor} = 0.18 W/m^2.K	12cm Insulation Layer- 0.035W/m.K

Similar to the previous study, first of all, the energy analyses had been done for single retrofit measures, then based on that analyzes, further studies have been done for combined measures. The energy consumption of each single retrofit measure is calculated and indicated in Figure 4.20. The results show that the opaque system improvements (S1-S6) are the most efficient single measures. Opaque system's

amendments can reduce the amount of PEC by more than 28% solely. Most of the glazing system retrofits (S7-S11) are not useful solely, it can decrease less than 5% of PEC while two of them (S12-S13) can reduce more than 5% of yearly PEC. Shading device application (S14 and S15) can reduce PEC by less than 3%. Among improvement scenarios for heating system (S16-S20), replacement of current boiler with condensing boiler (S19) can reduce PEC by more than 15% and reach to 164.7 kWh/m^2.a. Replacement of existing radiator system with heated floor (S18) can reduce 14% of yearly PEC. Replacement of current boiler with non-condensing boiler (S20) can reduce PEC by about 8%. Rest of heating system improvement measures (S16-S17) are not very efficient. The potential of PEC reduction in cooling system improvement's scenarios (S21-S23) is just 1.5%. Photovoltaic system addition (S24) can improve the PEC by about 15%. Lighting system improvement (S25) reduces the PEC by less than 3%. Opaque system improvements can reduce the heating system's PEC by about 50% while doubles the cooling system's PEC that are a little amount in compare with heating PEC (Figure 4.20).

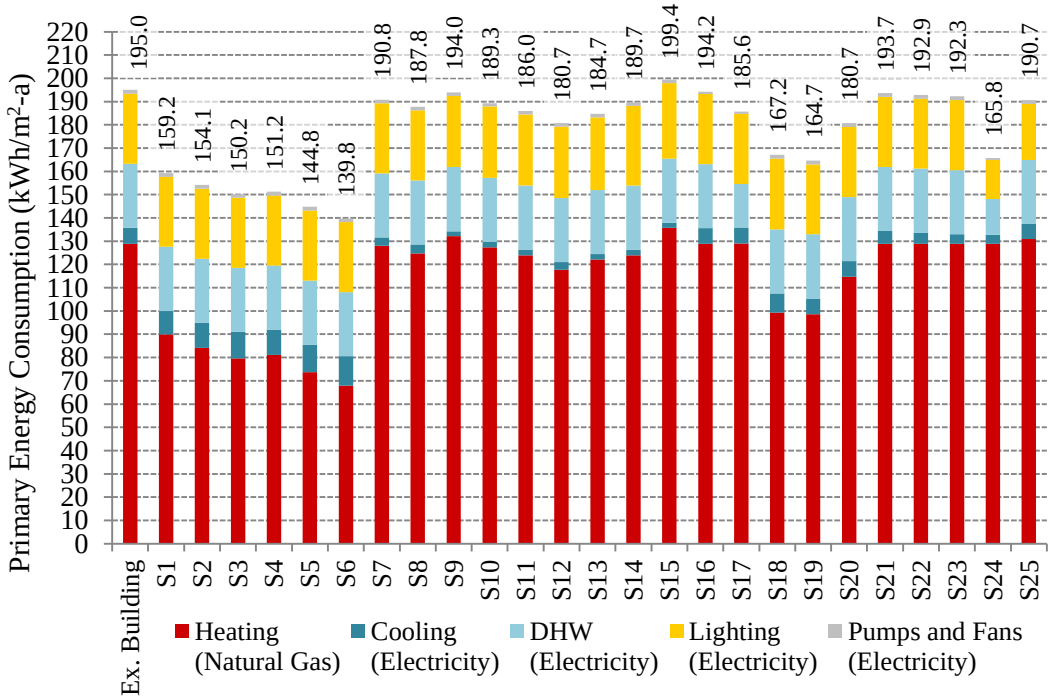

Figure 4.20 : Yearly PEC of each single measure of detached building in Erzurum.

The initial investment costs for opaque system amendments are illustrated in Table 4.20. When available, costs from three material producer are provided as unit price for

each measure (Table 4.20). The cost of the rest of single measures is indicated in Table 4.16. The related cost of combined measures is calculated based on this table as well.

Table 4.20 : Cost calculations for single retrofit measures of a detached building in Erzurum.

Acr.	Improved Component	Amount (m2 / piece)	Average unit Cost (TL)	Material Cost (TL)	Indirect Cost (TL)	TAX (TL)	Total Cost (TL)
S1	Wall	1191.53	30.92	36847.27	9211.82	8290.64	54349.72
S2	Wall	1191.53	37.05	44142.61	11035.65	9932.09	65110.35
S3	Wall	1191.53	45.44	54143.12	13535.78	12182.20	79861.11
S4	Wall	1191.53	30.92	46709.05	11677.26	10509.54	68895.84
	Roof	385.00	10.32				
	G.F.	357.00	16.50				
S5	Wall	1191.53	37.05	58864.31	14716.08	13244.47	86824.86
	Roof	385.00	14.50				
	G.F.	357.00	25.60				
S6	Wall	1191.53	45.44	75937.62	18984.41	17085.97	112007.99
	Roof	385.00	12.10				
	G.F.	357.00	48.00				

Cost per housing unit in Figure 4.21 indicates the amount of money that each family should pay for the actions. The third level of the wall and opaque system amendment (S3 & S6) together with the second level of opaque system improvement (S5) require a very high budget for each owner. From these measures, just S5 can be divided into the steps that have acceptable costs. Most of the glazing system enhancements (S7-S11) have less than 2270TL investment cost. The rest of the measures (S12-S13) have less than 3000TL cost. Shading device applications (S14-S15) together with heated floor application (S18) also provide owners with a very high payment for actions. Cooling system's improvements (S21-S23) are also expensive. PV application (S24) is an expensive measure but can be divided into some steps with acceptable initial investment costs. Replacement of existing boiler with condensing and non-condensing boiler (S19-S20), modification of existing heating system by adding the variable heat pump (S16) and replacement of existing lamps with LED lights (S25) are the most cheaper measures. Other measures seem to have the reasonable amount of payment while items with more than 2270TL cost need to pay more attention (Figure 4.21).

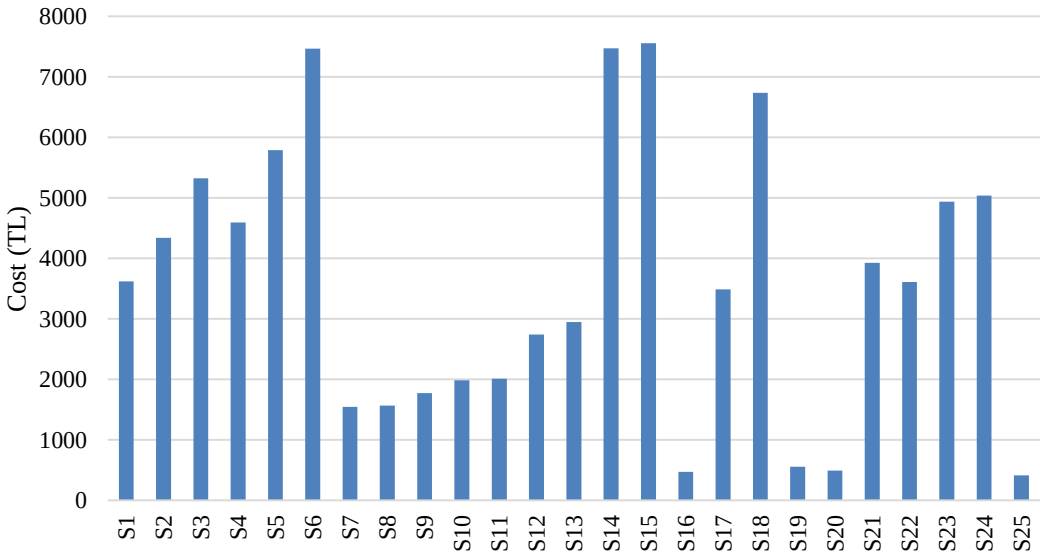

Figure 4.21 : Cost per flat for single retrofit measures (Detached-Erzurum).

The payback period for each single measure is calculated to determine its feasibility. Replacement of the existing boiler with condensing boiler (S19) by about one-year period is of the first rank while replacement of the existing boiler with non-condensing one (S20) and the lighting system amendment (S25) are located in the second and third position. All opaque system improvements (S1-S6), except the third level of whole opaque improvement (S6), have less than 10-year payback period. Rest of architectural measures (S7-S15) have more than ten years' payback period while some of the glazing system improvements (S8, S11, S12) have less than 15-year payback period. PV system application (S24) also have less than ten years' payback time (Figure 4.22).

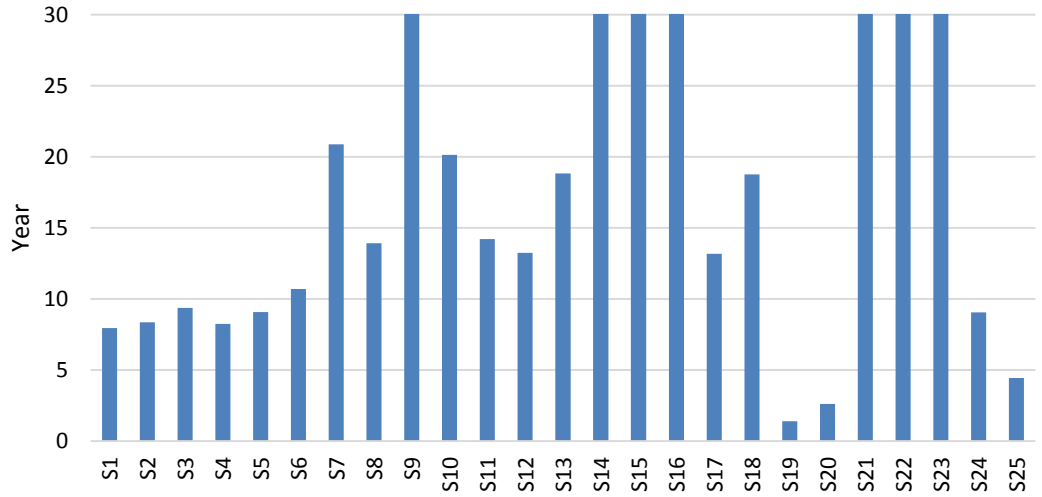

Figure 4.22 : The payback period of each single measure (Detached-Erzurum).

Figure 4.23 shows the amount of CO_2 emission of each single measure in Erzurum's case. It is possible to reach to about 26% of CO_2 emission saving by application of S6 that is the third level of opaque system improvement. Opaque system enhancements (S1-S6) are very effective than other improvements. The addition of PV system is also effective from CO_2 emission point of view. It can reduce 17% of total yearly emission. About 9 actions can provide about 10% CO_2 emission saving (Figure 4.23).

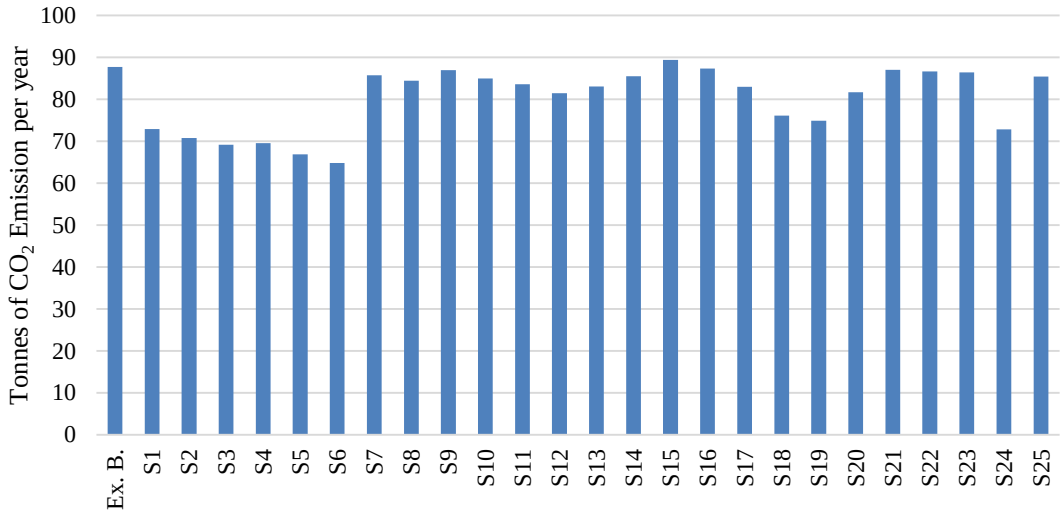

Figure 4.23 : CO_2 emission of each single measure (Detached-Erzurum).

The existing case study building has approximately 603 TL/m^2 global cost. The second level of whole opaque amendments (S5) with 524 TL/m^2 global cost and 144 kWh/m^2 PEC is located at the lowest point of the graph. Eight measures are located above case study building, hence, should be eliminated from further analyzes. Thus, the third level of glass improvement (S9), shading system applications (S14-S15), replacement of existing auxiliary system with variable heat pumps (S16), application of heated floor (S18) and improvements of existing cooling systems (S21-S23) had been excluded from analyzes. The third level of the wall and opaque system amendments (S3 and S6) are located above the second level of related amendments (S2 and S5), thus, are irrational to include in combined measures. From rest of glazing system improvements, first and fourth level (S7 and S10) have very close global cost to existing building while seventh level amendment (S13) have more global cost in compare with fifth level improvement. Hence, all of them are eliminated from further analyzes. The addition of solar collectors to the heating system (S17) is not reducing the global cost by a considerable amount and removed from further analyzes. Thus, the number of required simulations are reduced significantly (Figure 4.24).

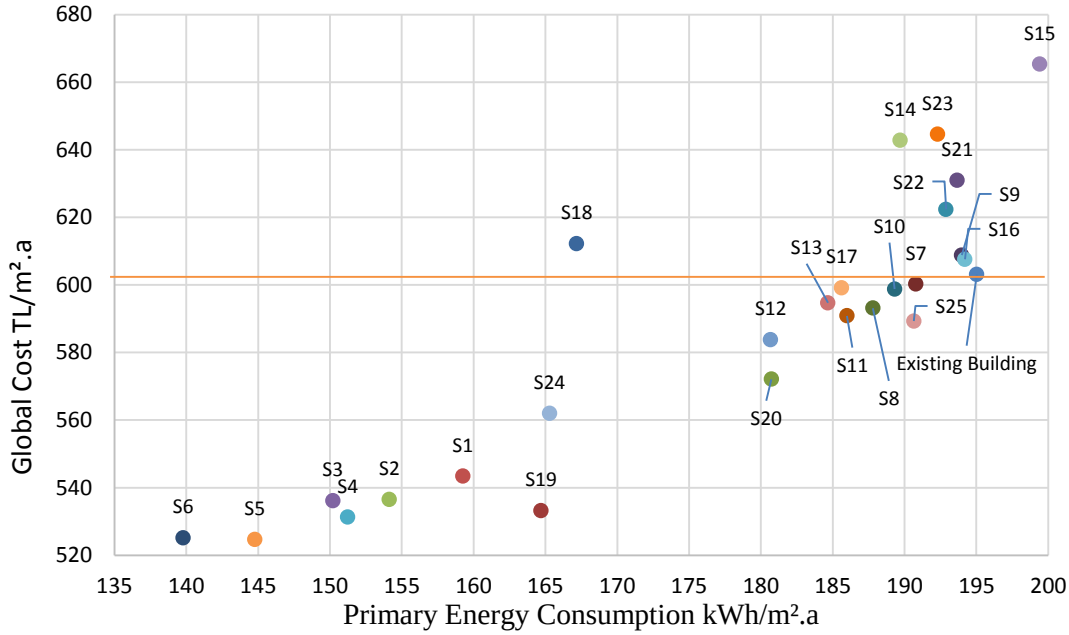

Figure 4.24 : The global cost vs. primary energy consumption graph for single measures. (Detached-Erzurum)

Rest of the single measures combined to define the retrofit packages. Similar to Antalya case, to reduce the number of simulations, first of all, architectural and mechanical system combination are identified and simulated. Then, lighting system improvements are applied to optimum architectural and mechanical system and after that PV applications are applied to them. Similar analyzes are done for related combined measures, and the necessary global cost vs. primary energy consumption graph is provided for these actions. From architectural and mechanical combination measures, five scenarios are at the optimum area. The characteristics of these optimum scenarios are indicated in Table 4.21. In general, when the second level of opaque system improvements (S5) together with the second, fifth and sixth level of glazing system amendments (S8, S11, S12) combined with existing boiler replacement by condensing one (S19), the retrofit will be located at the optimum area. Except these scenarios, combination of the sixth level of glazing enhancement (S12) and second level of the wall (S2) or first level of whole opaque improvements (S4) with S19 are at the optimum region. Furthermore, optimal architectural and mechanical system improvements can reduce global cost by approximately 22% and PEC by about 40% (Figure 4.25 and Table 4.21).

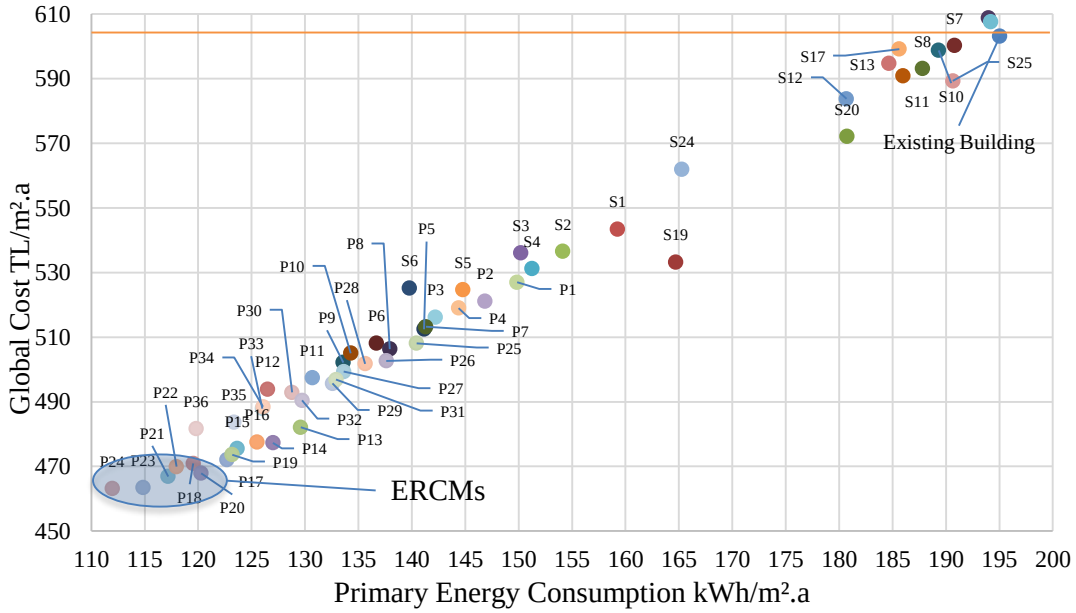

Figure 4.25 : The global cost vs. primary energy consumption graph for combined architectural and mechanical measures (Detached-Erzurum).

Table 4.21 : Energy efficiency measures that constitute the ERCMs (Detached-Erzurum).

Acr.	Energy Efficiency Measure (Architecture)	Energy Efficiency Measure (HVAC System)
P18	U_{Wall} 25% + 6th Glazing (S2+S12)	Condensing Boiler (S19)
P21	U_{Opaque} TS825 + 6th Glazing (S4+S12)	Condensing Boiler (S19)
P22	U_{opaque} 25% + 2th Glazing (S5+S8)	Condensing Boiler (S19)
P23	U_{opaque} 25% + 5th Glazing (S5+S11)	Condensing Boiler (S19)
P24	U_{opaque} 25% + 6th Glazing (S5+S12)	Condensing Boiler (S19)

By application of lighting system amendment and PV system to the ERCMs, it is possible to reach to about 410 TL/m^2 global cost and approximately 80 kWh/m^2 PEC. It means the cost-optimal scenarios can provide about 58% primary energy saving together with 32% global cost saving for the case study building (Figure 4.26).

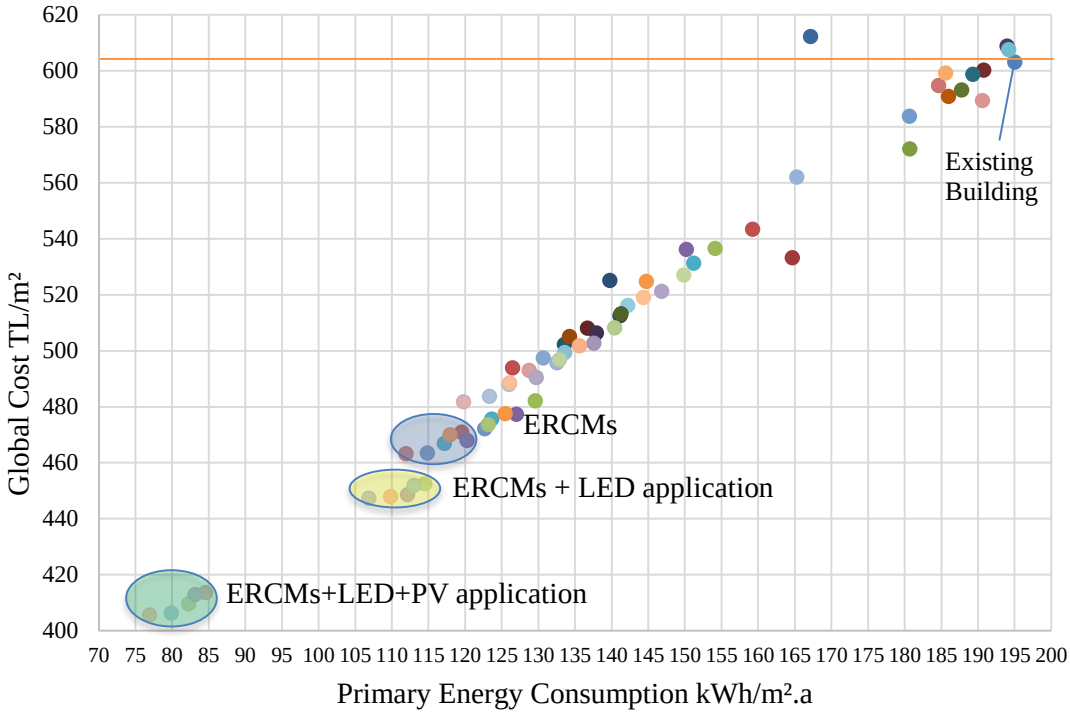

Figure 4.26 : The global cost vs. primary energy consumption graph for whole scenarios (Detached-Erzurum).

The initial investment cost and cost per flat of optimum cases are indicated in Table 4.22. As seen there, the contribution amount for each owner in all cases is more than the reasonable amount. Thus, all of them should be analyzed to apply as step-by-step retrofits. All optimum scenarios have about/less than eight years' payback period (Table 4.22).

Table 4.22 : Cost per flat and payback time for cost optimum scenarios. (Detached-Erzurum)

	Total Initial Investment Cost (TL)	Cost per Flat (TL)	Payback Period (yr.)
P18+LED+PV	196,351.04	13,090.07	7.86
P21+LED+PV	200,136.53	13,342.44	7.87
P22+LED+PV	200,434.58	13,362.31	7.96
P23+LED+PV	207,112.79	13,807.52	7.98
P24+LED+PV	218,065.55	14,537.70	8.25

4.5.1.3 Results of energy-cost analyses for the detached building located in Istanbul

Based on Table 4.8, a set of retrofit measures were created to apply to the case study building in Istanbul. Table 4.23 is representing the amount of insulation layers and glazing system types that had been implemented to the case study building as the single

retrofit measures (Table 4.23). For the glazing system, the descriptions available in Table 4.15 and for energy systems, the descriptions identified in Table 4.8 were used.

Table 4.23 : Description of single retrofit measures of architectural components for detached building in Istanbul.

Acr.	Values	Description
S1	U_{wall} = 0.57 W/m^2.K	3cm Insulation Layer- 0.035W/m.K
S2	U_{wall} = 0.40 W/m^2.K	6cm Insulation Layer- 0.035W/m.K
S3	U_{wall} = 0.27 W/m^2.K	10cm Insulation Layer- 0.035W/m.K
S4	U_{wall} = 0.57 W/m^2.K	3cm Insulation Layer- 0.035W/m.K
	U_{roof} = 0.38 W/m^2.K	4cm Insulation Layer- 0.035W/m.K
	U_{floor} = 0.57 W/m^2.K	3cm Insulation Layer- 0.035W/m.K
S5	U_{wall} = 0.40 W/m^2.K	6cm Insulation Layer- 0.035W/m.K
	U_{roof} = 0.28 W/m^2.K	7cm Insulation Layer- 0.035W/m.K
	U_{floor} = 0.40 W/m^2.K	5cm Insulation Layer- 0.035W/m.K
S6	U_{wall} = 0.27 W/m^2.K	10cm Insulation Layer- 0.035W/m.K
	U_{roof} = 0.19 W/m^2.K	12cm Insulation Layer- 0.035W/m.K
	U_{floor} = 0.27 W/m^2.K	9cm Insulation Layer- 0.035W/m.K

First of all, the energy analyses had been done for single retrofit measures. Then based on that analyzes, further studies have been done for combined measures. The energy consumption of each single retrofit measure is calculated and indicated in Figure 4.27. The results show that the whole opaque system retrofits (S4-S6) are more efficient than other architectural improvements (S1-S15) while wall retrofits (S1-S3) act similarly to opaque system retrofit. Opaque system's improvement can reduce the amount of PEC by more than 20% solely. Photovoltaic system addition (S24) is effective as much as opaque system enhancements. It can improve the PEC by about 18%. Glazing system retrofits (S7-S13) are not useful solely, it can decrease 8.5% of PEC at most. Shading device application (S14 and S15) can improve PEC by 4%. Among improvement scenarios for heating system (S16-S20), replacement of current boiler with condensing boiler (S19) can reduce PEC by more than 10% and reach to 128.4 kWh/m^2.a. The potential of PEC reduction in cooling system improvement's scenarios (S21-S23) is 6.5%. Lighting system improvement (S25) reduces the PEC by less than 4%. Opaque system improvements can reduce the heating system's PEC by about 50% while increase the cooling system's PEC by about 26% (Figure 4.27).

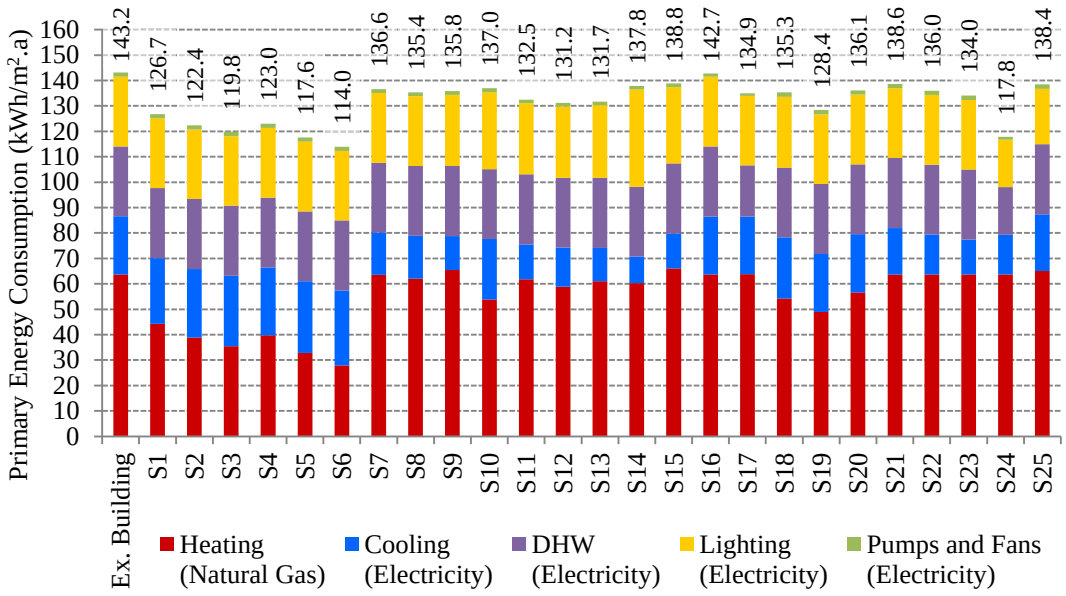

Figure 4.27 : Yearly PEC of each single measure of detached building in Istanbul.

The initial investment costs for opaque system improvement are illustrated in Table 4.24. When available, costs from three material producer are provided as unit price for each measure. In roof and floor retrofits, the cost of extra materials is added to unit costs as a constant value (Table 4.24). For rest of measures values indicated in Table 4.16 are used as the same measures are applied in Istanbul and Antalya. The related cost of combined measures is calculated based on these tables as well.

Table 4.24 : Cost calculations for single retrofit measures of the detached building in Istanbul.

Acr.	Improved Component	Amount (m^2 / piece)	Average unit Cost (TL)	Material Cost (TL)	Indirect Cost (TL)	TAX (TL)	Total Cost (TL)
S1	Wall	1191.53	24.11	28730.57	7182.64	6464.38	42377.59
S2	Wall	1191.53	30.92	36847.27	9211.82	8290.64	54349.72
S3	Wall	1191.53	52.96	63108.19	15777.05	14199.34	93084.59
S4	Wall	1191.53	24.11	37481.99	9370.50	8433.45	55285.94
	Roof	385.00	13.39				
	GF	357.00	10.07				
S5	Wall	1191.53	30.92	48486.17	12121.54	10909.39	71517.10
	Roof	385.00	17.88				
	GF	357.00	13.33				
S6	Wall	1191.53	52.96	78498.57	19624.64	17662.18	115785.39
	Roof	385.00	12.44				
	GF	357.00	29.70				

Cost per housing unit in Figure 4.28 indicates the amount of money that each family should pay for the actions. Third level of the wall and opaque system amendment (S3 & S6) require a very high budget for each owner. Shading device applications (S14-S15) together with heated floor application (S18) also provide owners with a huge payment for actions. Replacement of existing boiler with condensing and non-condensing boiler (S19-S20), modification of existing heating system by adding the variable heat pump (S16) and replacement of existing lamps with LED lamps are the most cheaper measures. Other measures seem to have the reasonable amount of payment or can be applied by one-year postponement while items with more than 2270TL cost need to pay more attention (Figure 4.28).

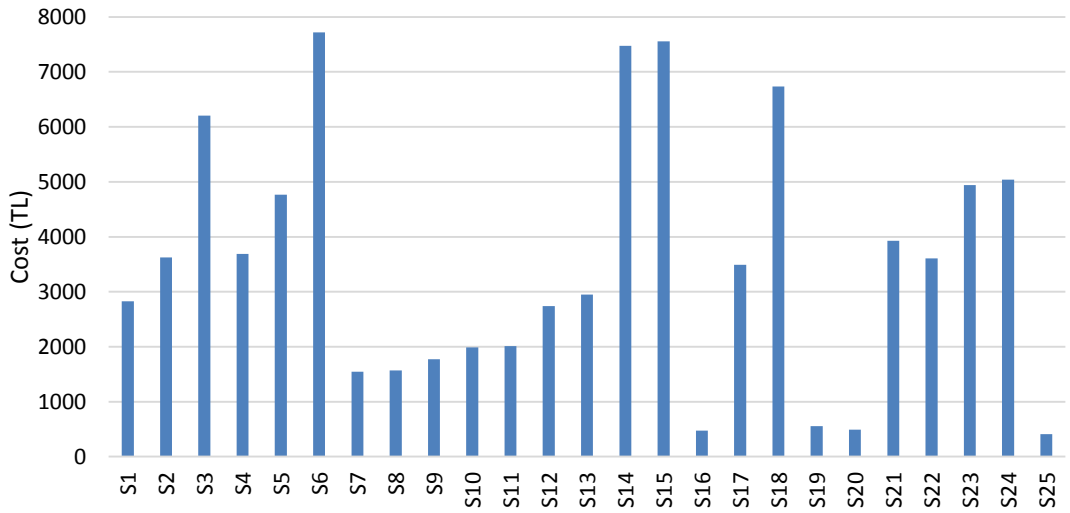

Figure 4.28 : Cost per Flat for Single Retrofit Measures (Detached-Istanbul).

The payback period for each single measure is calculated to determine its feasibility. Replacement of the existing boiler with condensing boiler (S19) by less than a three-year period is in the first rank while the lighting system amendment (S25) and replacement of the existing boiler with non-condensing one (S20) are located in the second and third position. From architectural improvements (S1-S15) just the fifth level of glass improvement (S11) has about 10-year payback period while most of the measures have less than 15-year payback period. PV system application (S24) also have proper payback time (Figure 4.29).

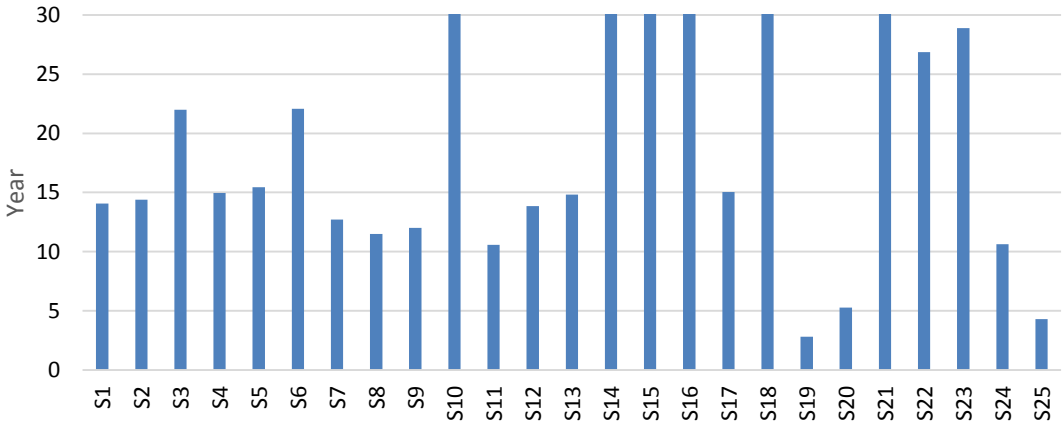

Figure 4.29 : The payback period of each single measure (Detached-Istanbul).

Figure 4.30 shows the amount of CO_2 emission of each single measure. It is possible to reach to about 24% of CO_2 emission saving by application of S6 that is the third level of opaque system improvement. Replacement of the existing boiler with condensing boiler (S19) and second level of opaque system amendment (S5) have more or less similar impact. About 9 actions can provide approximately 10% CO_2 emission saving (Figure 4.30).

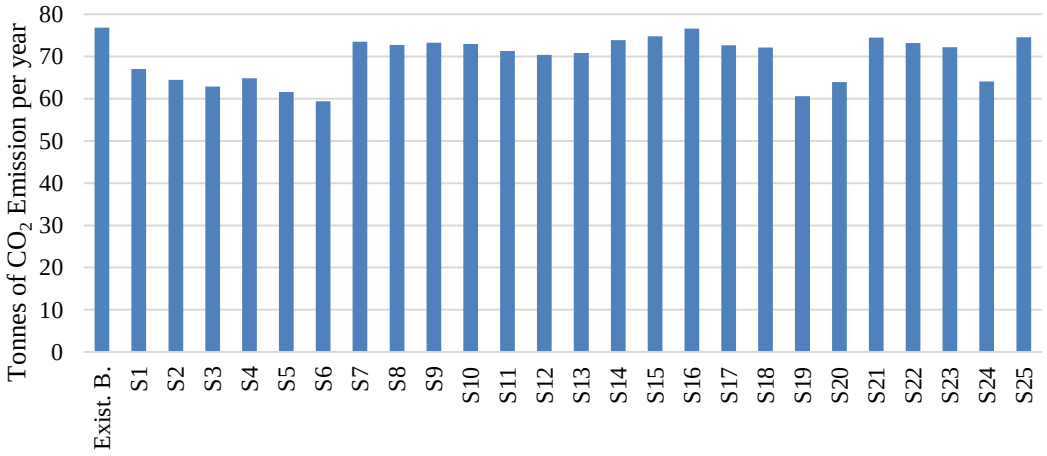

Figure 4.30 : CO_2 Emission of each single measure (Detached-Istanbul).

The existing case study building has approximately 490 TL/m^2 global cost. Replacement of the existing boiler with condensing boiler (S19) with 452 TL/m^2 global cost and 128 kWh/m^2 PEC is located at the lowest point of the graph. Eight measures are located above case study building, hence, should be eliminated from further analyzes. Thus, cooling system improvements (S21-23) and shading system applications (S14-S15) together with the application of heated floor (S18), replacement of existing heat pump with variable heat pump (S16) and fifth level of

glass improvement (S10) had been excluded from analyzes. The third level of the wall and opaque system amendments (S3 and S6) are located above the second level of related amendments, thus, are irrational to include in combined measures. From glazing system improvements, first, the second, third and fifth level of the amendment (S7-S9 and S11) are decreasing the amount of global cost and PEC of existing case study building. Sixth and seventh level of glass improvements (S12-S13) have more global cost in comparison with S11, hence, will not lead to reaching the lowest point of the whole measures global cost vs. primary energy consumption graph and should be eliminated from further analyzes. Adding solar collectors to the heating system (S17) is not reducing the global cost and removed from further analyzes. Thus, the number of required simulations is reduced significantly (Figure 4.31).

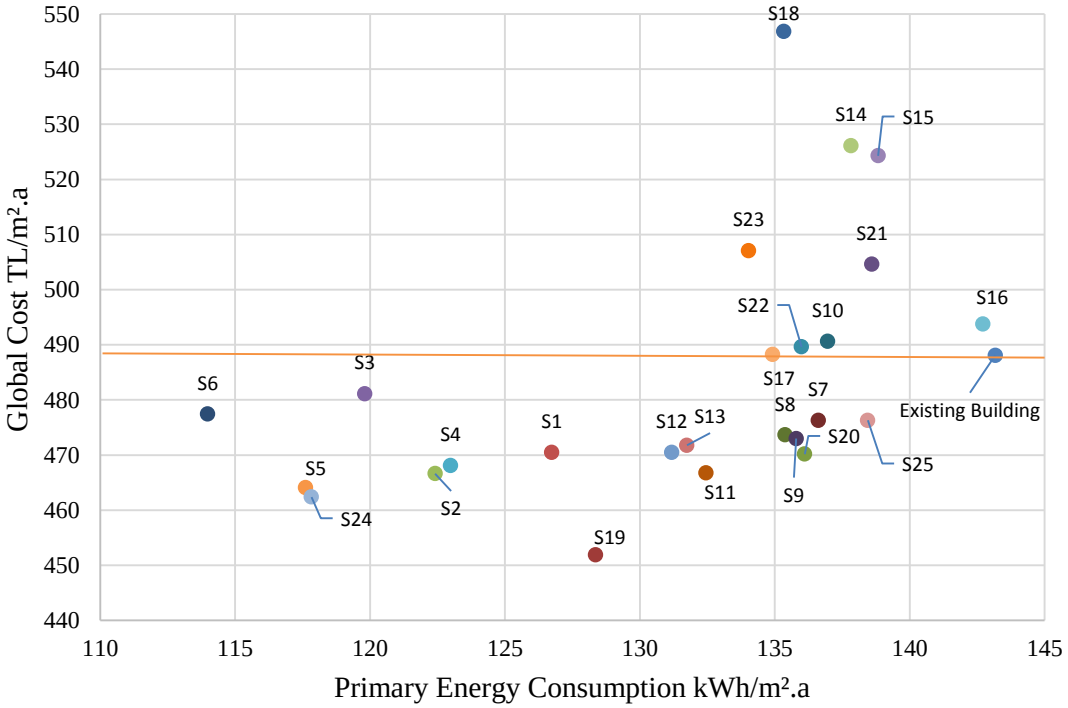

Figure 4.31 : The global cost vs. primary energy consumption graph for single measures (Detached-Istanbul).

Rest of the single measures should be combined to define the retrofit packages. To reduce the number of simulations as indicated in the related methodology section, first of all, architectural and mechanical system combination are identified and analyzed. From architectural and mechanical combination measures, P13, P14, P15, and P16 are at the lowest point of the graph that is indicating the ERCMs. P13 is a mix of the second level of exterior wall improvements with the fifth level of glazing system amendment and replacement of the existing boiler with a condensing boiler. P14 is a

combination of the first level of opaque system improvements with the fifth level of glazing system amendment and replacement of the existing boiler with a condensing boiler. P15 is a combination of the second level of opaque system improvements with the third level of glazing system amendment and replacement of the existing boiler with a condensing boiler. P16 is a combination of the second level of opaque system improvements with the fifth level of glazing system amendment and replacement of the existing boiler with a condensing boiler. As the third level of glass improvement has about 1.5 years more payback period than the fifth level of glass amendment, the P15 is eliminated from further analyzes. In general, ERCMs can reduce global cost by approximately 15% and PEC by about 32% (Figure 4.32 and Table 4.25).

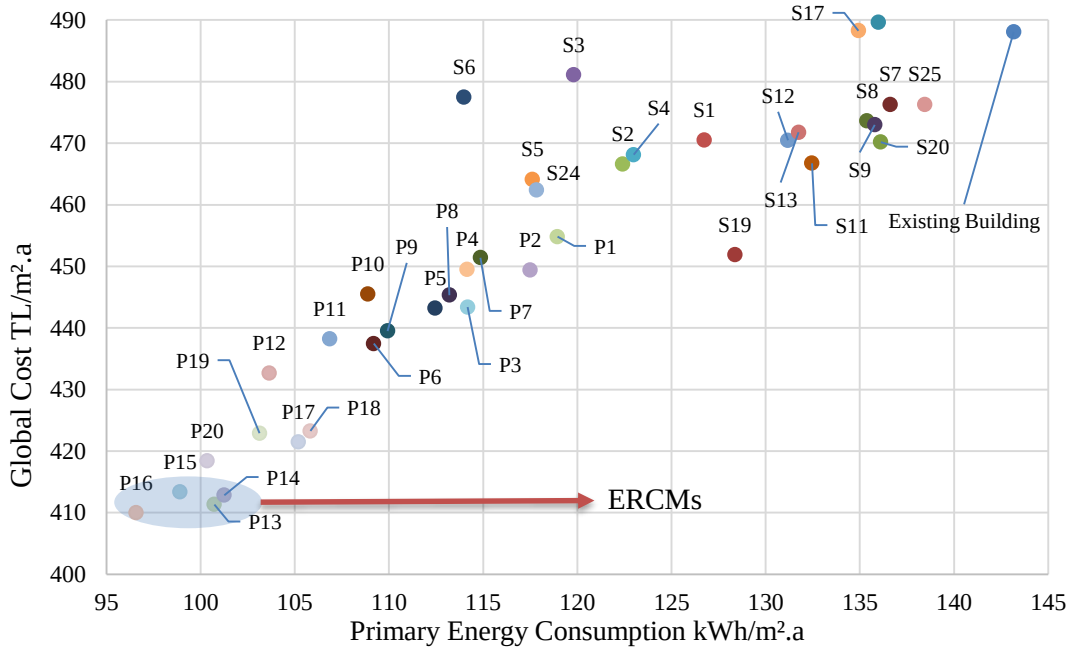

Figure 4.32 : The global cost vs. primary energy consumption graph for the combinations of architectural and mechanical measures (Detached-Istanbul).

Table 4.25 : Energy efficiency measures that constitute the ERCMs (Detached-Istanbul).

Acr.	Energy Efficiency Measure (Architecture)	Energy Efficiency Measure (HVAC System)
P13	U_{Wall} 25% + 5th Glazing (S2+S11)	Condensing Boiler (S19)
P14	U_{Opaque} TS825 + 5th Glazing (S4+S11)	Condensing Boiler (S19)
P16	U_{opaque} 25% + 5th Glazing (S5+S11)	Condensing Boiler (S19)

Then, lighting system improvements are applied to the ERCMs and after that PV applications are implemented to those combinations. Similar analyzes are done for

related combined measures, and the necessary global cost vs. primary energy consumption graph is provided for these actions. By application of lighting systems' amendment and PV system to the ERCMs, it is possible to reach to about 380 TL/m^2 global cost and approximately 70 kWh/m^2 PEC. As these combinations are located at the lowest point of the related graph, the cost-optimal scenarios are consisted from the combination of ERCMs with LED and PV application. Thus, the cost-optimal scenarios can provide more than 50% primary energy saving together with 22% global cost saving for the case study building (Figure 4.33).

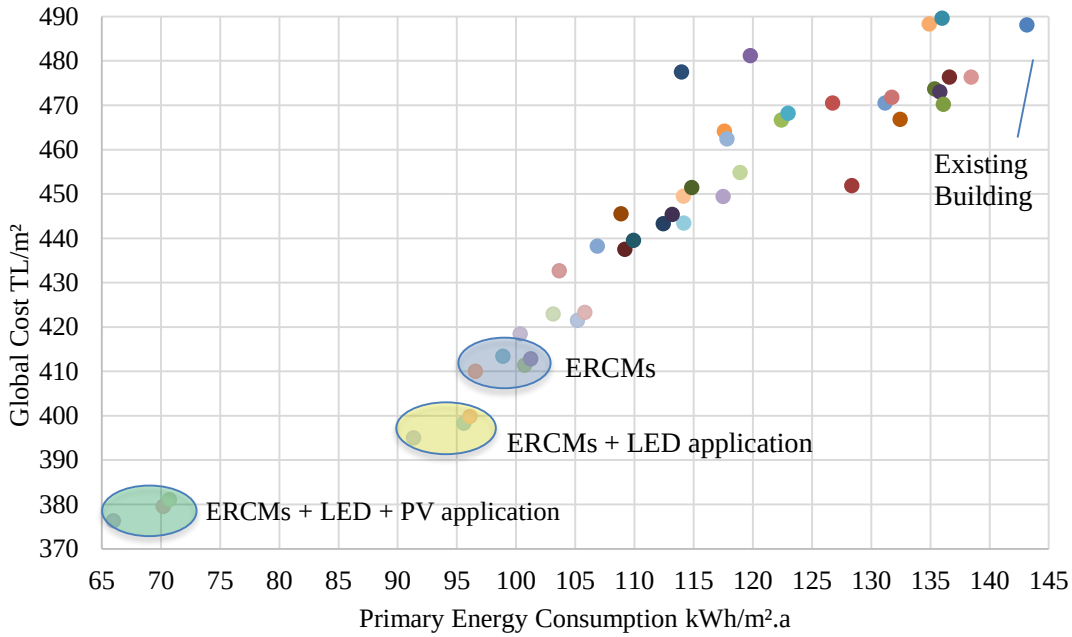

Figure 4.33 : The global cost vs. primary energy consumption graph for whole combined measures (Detached-Istanbul).

The initial investment cost and cost per flat of optimum cases are indicated in Table 4.26. As seen there, the contribution amount for each owner in all cases is more than the payable amount. Thus, all of them should be analyzed to apply as step-by-step retrofits. All optimum scenarios have less than ten years' payback period. (Table 4.26)

Table 4.26 : Cost per flat and payback time for the cost-optimum scenarios (Detached-Istanbul).

	Total Initial Investment Cost (TL)	Cost per Flat (TL)	Payback Period (yr.)
P13+LED+PV	164353.95	10956.93	9.34
P14+LED+PV	165290.17	11019.34	9.44
P16+LED+PV	177953.01	11863.53	9.69

4.5.2 Row Building

Results of energy and cost analyses for the row buildings located in Antalya, Erzurum and Istanbul are as follows:

4.5.2.1 Results of energy-cost analyses for the row building located in Antalya

Based on Table 4.9, a set of retrofit measures were created to apply to the case study building in Antalya. Table 4.27 is representing the amount of insulation layer that had been implemented to the case study building as the single retrofit measures. For the glazing system, the descriptions available in Table 4.15 and for the energy systems, the descriptions identified in Table 4.9 were used. (Table 4.27)

Table 4.27 : Description of single retrofit measures of opaque components. (Row-Antalya)

Acr.	Values	Description
S1	U_{wall}= 0.50 W/m^{2}K	3cm Insulation 0.035W/mK
S2	U_{wall}= 0.33 W/m^{2}K	7cm Insulation 0.035W/mK
S3	U_{wall}= 0.50 W/m^{2}K	3cm Insulation Layer 0.035W/mK
	U_{roof}= 0.32 W/m^{2}K	4cm Insulation Layer 0.04W/mK
	U_{floor}= 0.50 W/m^{2}K	3cm Insulation Layer 0.035W/mK
S4	U_{wall}= 0.33 W/m^{2}K	7cm Insulation Layer 0.035W/mK
	U_{roof}= 0.21 W/m^{2}K	10cm Insulation Layer 0.04W/mK
	U_{floor}= 0.33 W/m^{2}K	6cm Insulation Layer 0.035W/mK

First of all, the energy analyses had been done for single retrofit measures, then based on that analyzes. Further, analyzes have been done for combined measures. The primary energy consumption of each single retrofit measure is calculated and indicated in Figure 4.34. The results show that PV system application (S24) is more efficient than all other actions. It can reduce the PEC by 25%. In contrast to the detached building, the opaque system retrofits (S1-S4) are not very efficient. Glazing system improvements (S5-S11) are more effective among architectural improvements measures (S1-S13), they can reduce PEC by at most 12%. Shading device application (S12-S13) can improve PEC by 5% mostly. The reason is that, however, shading device applications are reducing the amount of cooling system PEC by about 36%, they increase the amount of lighting PEC by 63% at the same time. Solar collector application (S15) can decrease 15% of PEC. Replacement of radiator system with heated floor (S16) can reduce 12% of PEC. As together with necessary heating energy

the DHW energy of the building are provided by the individual system, combi-boiler, pumps and fans energy consumption is very high. Thus, the replacement of the existing boiler with condensing one or central system (S17-S19) can reduce PEC in a significant amount. The potential of PEC reduction, in this case, is more than 20%. Cooling system amendments (S20-S21) have more than 15% PEC reduction potential. Lighting system improvement (S23) reduces the PEC by about 5%. Glazing system improvements sometimes will have doubled the heating system's PEC while decrease the cooling system's PEC by about 32% (Figure 4.34).

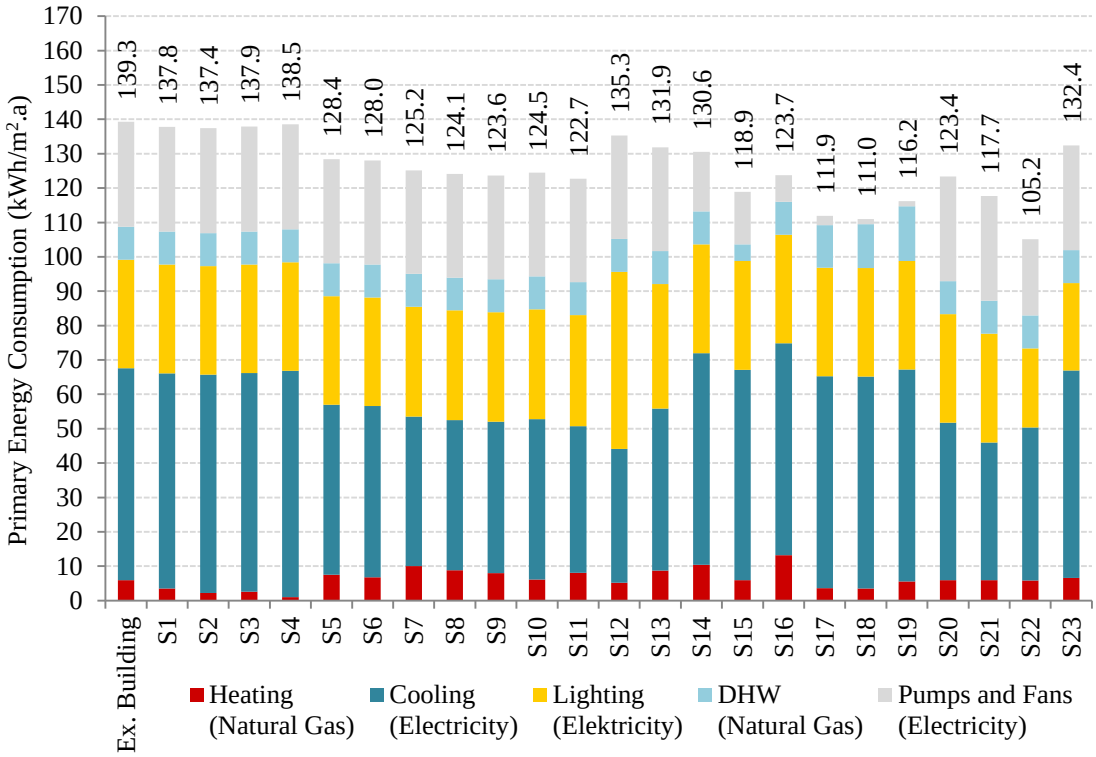

Figure 4.34 : Yearly PEC of single retrofit measure (Row-Antalya).

The initial investment cost for each single action is illustrated in Table 4.28. When available, costs from three material producer are provided as unit price for each measure. In roof and floor retrofits, the cost of extra materials is added to unit costs as a constant value (Table 4.28). The related cost of combined measures is calculated based on this table as well.

Table 4.28 : Cost calculations for single retrofit measures of row building in Antalya.

Acr.	Improved Component	Amount (m^2 / piece)	Average unit Cost (TL)	Material Cost (TL)	Indirect Cost (TL)	TAX (TL)	Total Cost (TL)
S1	Wall	740.7	24.11	17860.01	4465.00	4018.50	26343.51
S2	Wall	740.7	30.92	22905.65	5726.41	5153.77	33785.84
S3	Wall	740.7	24.11	21979.57	5494.89	4945.40	32419.87
	Roof	195.6	13.39				
	GF	168.9	8.88				
S4	Wall	740.7	30.92	28304.67	7076.17	6368.55	41749.39
	Roof	195.6	8.26				
	GF	168.9	22.40				
S5	Glass	162.7	46.78	7610.29	1902.57	1712.32	11225.18
S6	Glass	162.7	47.43	7716.05	1929.01	1736.11	11381.17
S7	Glass	162.7	53.70	8736.99	2184.25	1965.82	12887.06
S8	Glass	162.7	60.15	9786.41	2446.60	2201.94	14434.95
S9	Glass	162.7	60.90	9908.43	2477.11	2229.40	14614.93
S10	Glass	162.7	83.00	13504.10	3376.03	3038.42	19918.55
S11	Glass	162.7	89.30	14529.11	3632.28	3269.05	21430.44
S12	S.D.	1	47160.72	47160.72	11790.18	10611.16	69562.06
S13	S.D.	1	48274.98	48274.98	12068.74	10861.87	71205.59
S14	VHP	10	320.00	3200.00	800.00	720.00	4720.00
S15	SC	10	2364.77	23647.65	5911.91	5320.72	34880.29
S16	HF	10	4566.75	45667.50	11416.87	10275.18	67359.55
S17	Con. Combi-Boiler	10	1529.72	15297.2	3824.30	2753.49	21875
S18	Con. Boiler	1	17178.6	17178.63	4294.65	3092.14	24565.44
S19	Non-Con. Boiler	1	6082.53	15469.85	3867.46	2784.56	22121.87
S20	AC COP3.5	10	2446.60	24466.00	6116.5	4403.88	34986.38
S21	AC COP4.0	10	3348.30	33483.00	8370.75	6026.94	47880.69
S22	PV	30	1220.27	36608.10	9152.02	8236.82	53996.94
S23	LED	160	14.00	2240.00	560.00	504.00	3304.00

Figure 4.35 indicates the amount of money that each family should pay for the actions. Shading device applications (S12-S13) together with solar collector application (S15), heated floor application (S16), PV application (S22) and replacement of current air conditioner with High-Efficiency ones with COP=4.0 (S21) provide owners with a very high payment for actions. From these measures, just PV application can be considered to use in step-by-step retrofit as it can be divided into some steps with the desirable cost for owners. Replacement of existing lamps with LED lights (S25), modification of existing heating system by adding the variable heat pump (S14) and replacement of existing combi-boiler with central condensing and non-condensing boiler (S18-S19) are the most cheaper measures respectively. Other measures seem to have the reasonable amount of payment while items with more than 2270TL cost need to pay more attention (Figure 4.35).

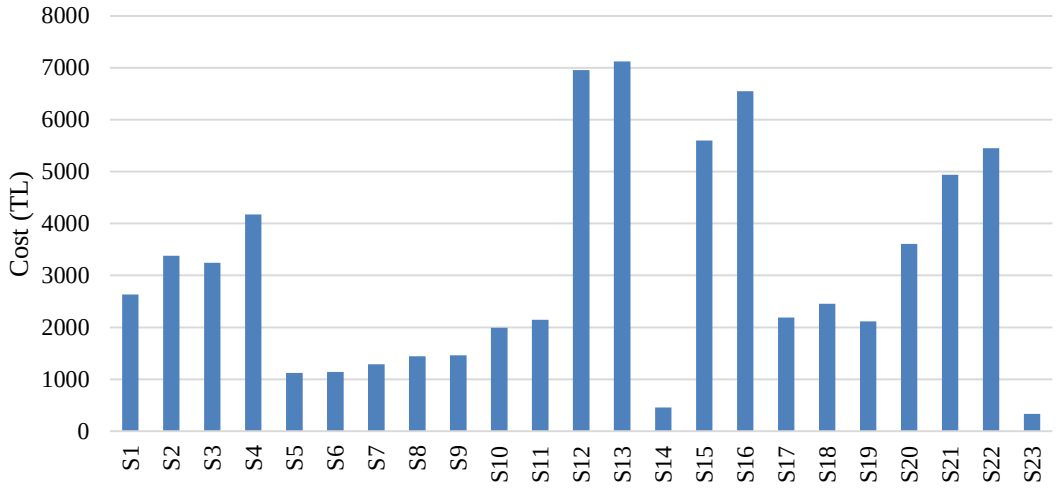

Figure 4.35 : Cost per flat for single retrofit measures (Row-Antalya).

The payback period for each single measure is calculated to determine its feasibility. The modification of existing heating system by adding the variable heat pump (S14) and the replacement of the existing lamps with LED ones (S23) by less than four-year periods are in the first rank while the replacement of existing combi-boiler with condensing one (S17) is located in the second position. Some of the glazing system improvements (S7-S9) and the replacement of existing combi-boiler with central condensing and non-condensing boiler (S18-S19) are located in the third rank simultaneously. From architectural improvement measures (S1-S13), opaque system enhancements (S1-S4) have very high payback periods while almost all of glazing system enhancements (S5-S11) have less than 10-year payback periods (Figure 4.36).

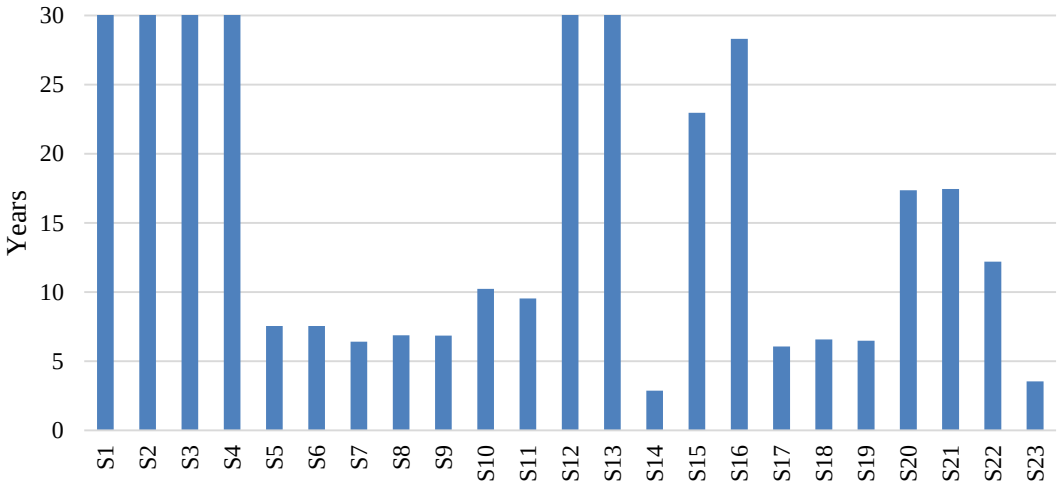

Figure 4.36 : The payback period of each single measure (Row-Antalya).

Figure 4.37 shows the amount of CO_2 emission of each single measure. It is possible to reach to about 25% of CO_2 emission saving by application of S22 that is the PV system application. The replacement of existing combi-boiler with central condensing boiler (S18) will lead to about 20% CO_2 emission saving. About 13 actions can provide more than 10% CO_2 emission saving (Figure 4.37).

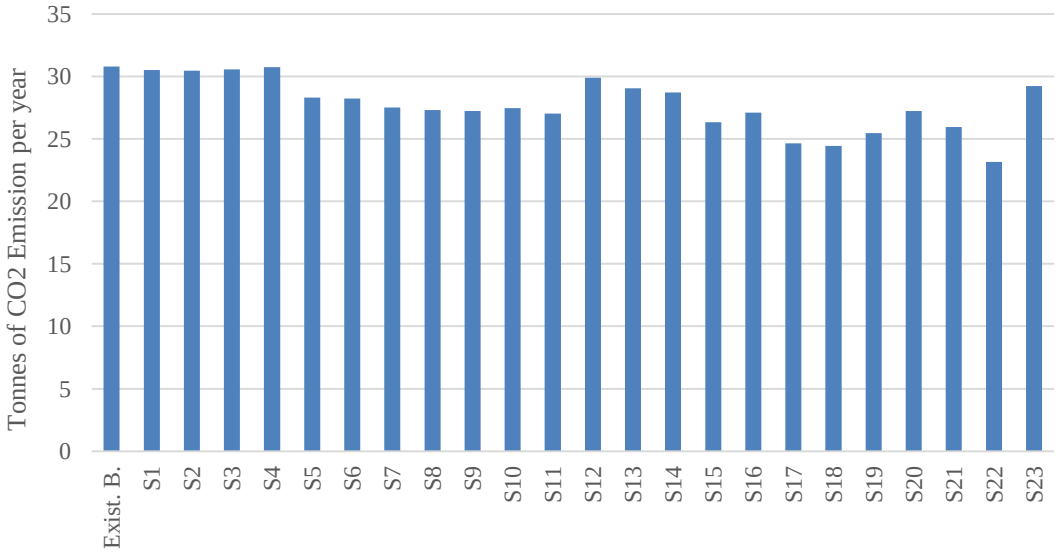

Figure 4.37 : CO_2 Emission of each single measure (Row-Antalya).

The existing case study building has approximately 549 TL/m^2 global cost. Replacement of the existing combi-boiler with central condensing boiler (S18) with 470 TL/m^2 global cost and 111 kWh/m^2 PEC is located at the lowest point of the graph. Nine measures are located above case study building, hence, should be eliminated from further analyzes. Thus, wall and whole opaque system amendments (S1-S4), shading

system applications (S12-S13), solar collector application (S15), replacement of radiator system with heated floor (S16) together with the replacement of air conditioner with High-Efficient one that has 4.0 COP (S21) had been excluded from further analyzes. Glazing system improvements, first to the fifth level of the amendment (S7-S11) are decreasing the amount of global cost and PEC of existing case study building. Sixth and seventh level of glass improvements (S10-S11) have more global cost in comparison with S9, hence, will not lead to reaching the lowest point of the combined measures global cost vs. primary energy consumption graph and should be eliminated from further analyzes. Thus, the number of required simulations is reduced significantly (Figure 4.38).

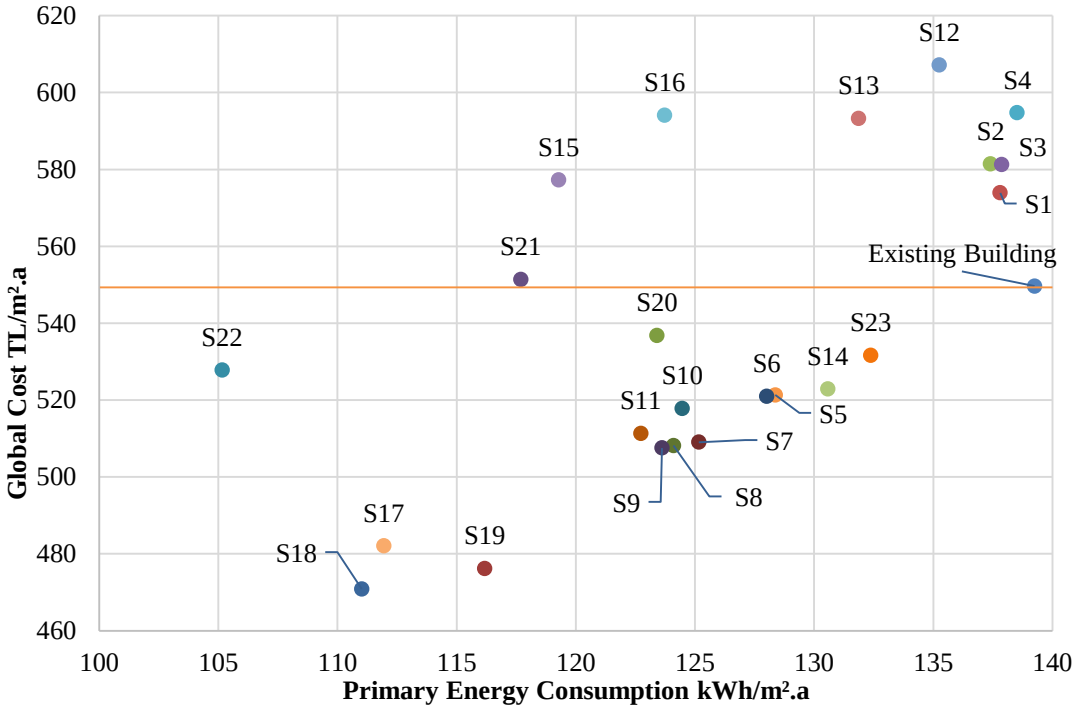

Figure 4.38 : The global cost vs. primary energy consumption graph for single measures (Row-Antalya).

Rest of the single measures combined to define the retrofit packages. To reduce the number of simulations, first of all, architectural and mechanical systems' combinations are identified and analyzed. In this case, the architectural improvement measures are limited to just glazing system amendments as indicated before. From architectural and mechanical combination measures, six scenarios are ERCMs. The characteristics of the ERCMs scenarios are given in table 4.29. In general, when the third, fourth and fifth level of glazing system amendments combined with central condensing boiler

application with or without the first level of cooling system enhancement, the retrofit measures will be ERCMs. Moreover, ERCMs can reduce global cost by approximately 25% and PEC by about 42% (Figure 4.39 and Table 4.29).

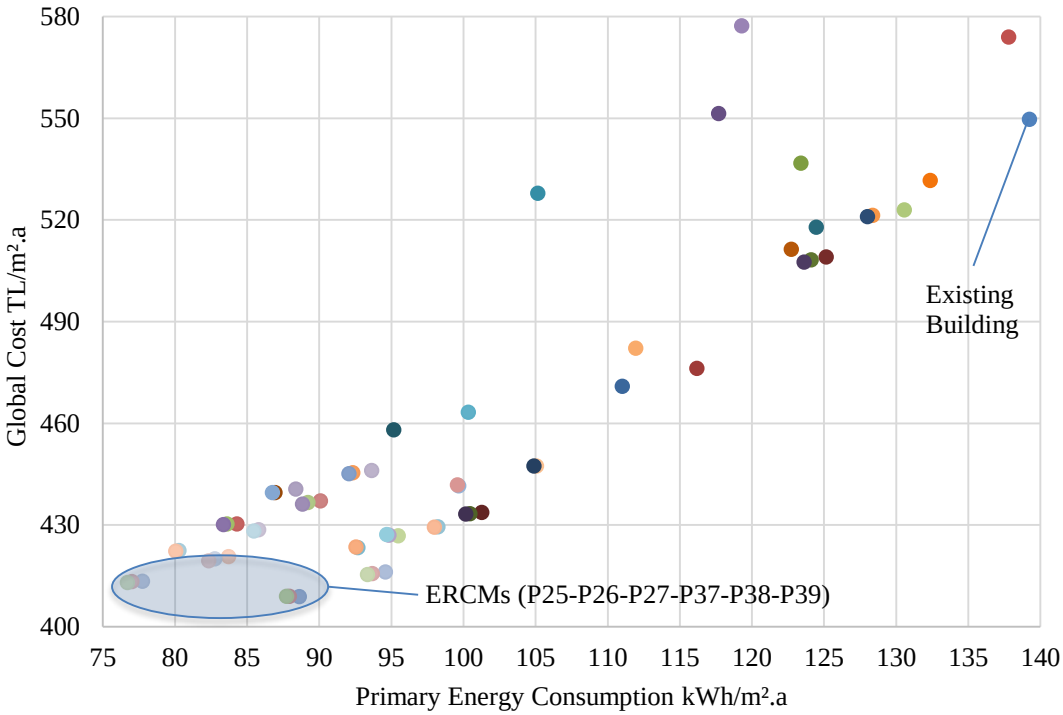

Figure 4.39 : The global cost vs. primary energy consumption graph for the combination architectural and mechanical measures (Row-Antalya).

Table 4.29 : Energy efficiency measures that constitute the ERCMs (Row-Antalya).

Acr.	Energy Efficiency Measure (Architecture)	Energy Efficiency Measure (HVAC System)
P25	3th Glazing (S7)	Condensing Central Boiler (S18)
P26	4th Glazing (S8)	Condensing Central Boiler (S18)
P27	5th Glazing (S9)	Condensing Central Boiler (S18)
P37	3th Glazing (S7)	Cond. Central Boiler + Coil COP = 3.5 (S18+S20)
P38	4th Glazing (S8)	Cond. Central Boiler + Coil COP = 3.5 (S18+S20)
P39	5th Glazing (S9)	Cond. Central Boiler + Coil COP = 3.5 (S18+S20)

Then, lighting system improvements are added to the ERCMs and after that PV applications are applied to the combinations. Similar analyzes are done for related combined measures, and the necessary global cost vs. primary energy consumption graph is drawn for these actions. By application of lighting system amendment and PV system to the ERCMS, it is possible to reach to approximately 375 TL/m^2 global cost

and in average about 42.5 kWh/m^2 PEC. Similar to previous cases, these combinations are located at the lowest point of the graph so they are cost-optimal measures for this building. They can provide more than 70% primary energy saving together with 32% global cost saving for the case study building (Figure 4.40).

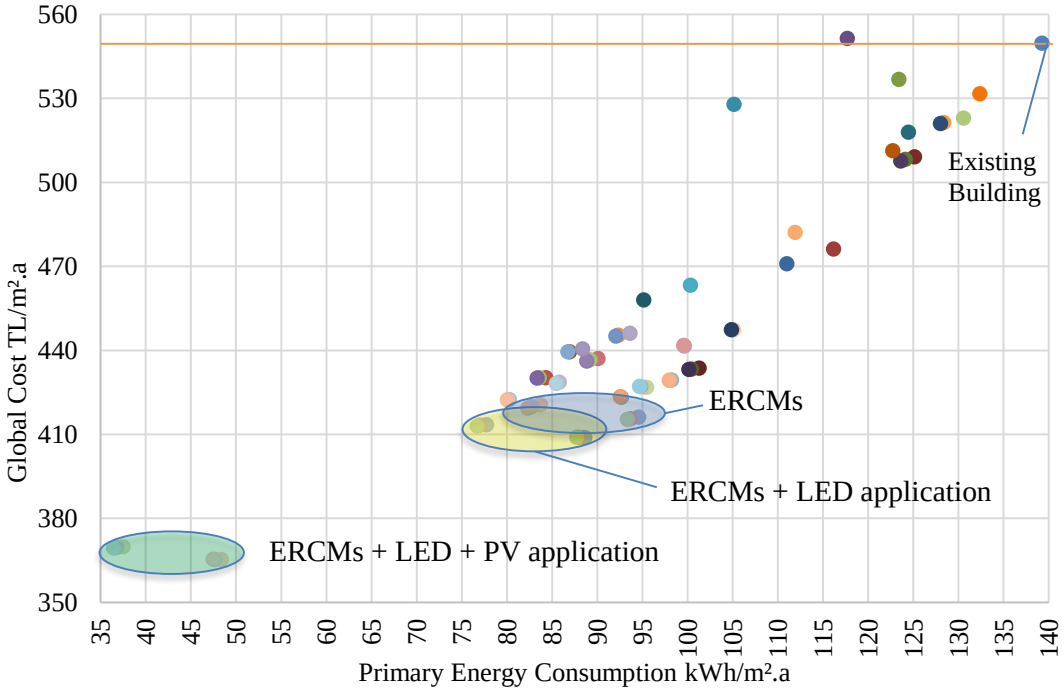

Figure 4.40 : The global cost vs. primary energy consumption graph for whole single and combined scenarios (Row-Antalya).

The initial investment cost and cost per flat of the cost-optimum cases are indicated in Table 4.30. As seen there, the contribution amount for each owner in all cases is more than the reasonable amount. Thus, all of them should be analyzed to apply as step-by-step retrofits. All scenarios have less than ten years' payback period (Table 4.30).

Table 4.30 : Cost per flat and payback time of the cost optimum scenarios (Row-Antalya).

	Total Initial Investment Cost (TL)	Cost per Flat (TL)	Payback Period (yr.)
P25+LED+PV	131,355.91	13,135.59	9.73
P26+LED+PV	132,903.79	13,290.38	9.80
P27+LED+PV	133,083.78	13,308.38	9.80
P37+LED+PV	95,268.51	9,526.85	7.89
P38+LED+PV	96,816.39	9,681.64	7.98
P39+LED+PV	96,996.38	9,699.64	8.00

4.5.2.2 Results of energy-cost analyses for the row building located in Erzurum

Based on Table 4.9, a set of retrofit measures were created to apply to the case study building in Erzurum. Table 4.31 is representing the amount of insulation layers that had been implemented to the case study building as the single retrofit measures (Table 4.31). For the glazing system, the descriptions available in Table 4.15 and for the energy systems, the descriptions identified in Table 4.9 are used.

Table 4.31 : Description of single retrofit measures of opaque components for the row building in Erzurum.

Acr.	Values	Description
S1	U_{wall} = 0.27 W/m^2.K	4cm Insulation Layer- 0.035W/m.K
S2	U_{wall} = 0.18 W/m^2.K	7cm Insulation Layer- 0.03W/m.K
S3	U_{wall} = 0.27 W/m^2.K	4cm Insulation Layer- 0.035W/m.K
	U_{roof} = 0.16 W/m^2.K	5cm Insulation Layer- 0.035W/m.K
	U_{floor} = 0.27 W/m^2.K	4cm Insulation Layer- 0.035W/m.K
S4	U_{wall} = 0.18 W/m^2.K	7cm Insulation Layer- 0.03W/m.K
	U_{roof} = 0.11 W/m^2.K	12cm Insulation Layer- 0.035W/m.K
	U_{floor} = 0.18 W/m^2.K	7cm Insulation Layer- 0.035W/m.K

Similar to previous studies, first of all, the energy analyses had been done for single retrofit measures, then based on that analyzes, further analyzes have been done for combined measures. The energy consumption of each single retrofit measure is calculated and indicated in Figure 4.41. The results show that the replacement of existing combi-boilers by central condensing boiler (S18) is the most efficient single measure. It can reduce the PEC by 33% and is following by two of other heating system improvements (S17 and S19). The replacement of radiator system by heated floor system (S16) and PV system application (S22) can provide about 20% PEC saving. Replacement of existing heat pumps with variable ones (S14) can reduce the PEC by about 10%. Architectural system improvements (S1-S13) have more or less similar influence on PEC. In the best condition, they can decrease PEC by 10%. External drop curtain application (S13) and third level of glazing system improvement (S7) will lead to increase in PEC. Lighting system improvement (S25) reduces the PEC by 3% (Figure 4.41).

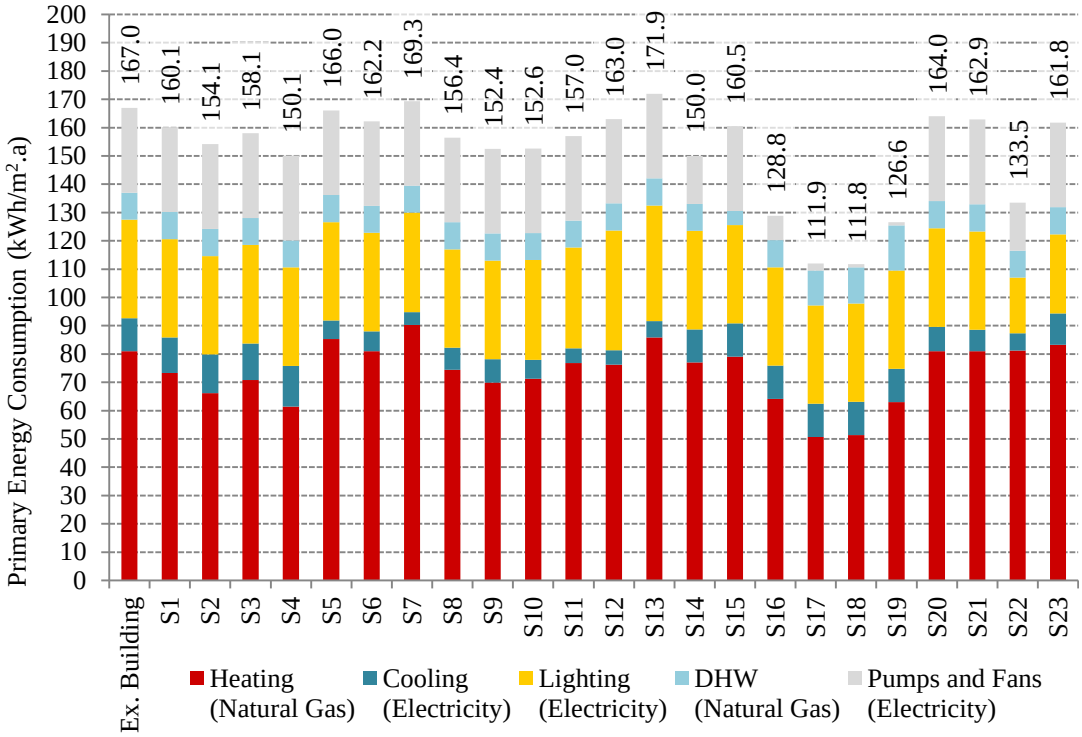

Figure 4.41 : Yearly PEC of each single measure of the row building in Erzurum.

The initial investment costs for opaque system improvements are illustrated in Table 4.32. When available, costs from three material producer are provided as unit price for each measure (Table 4.32). Costs related to the rest of measures' applications are indicated in Table 4.28. The related cost of combined measures is calculated based on this table as well.

Table 4.32 : Cost calculations for the single retrofit measures of the row building in Erzurum.

Acr.	Improved Component	Amount (m2 / piece)	Average unit Cost (TL)	Material Cost (TL)	Indirect Cost (TL)	TAX (TL)	Total Cost (TL)
S1	Wall	740.7	28.70	21257.35	5314.34	4782.90	31354.59
S2	Wall	740.7	52.96	39230.43	9807.61	8826.85	57864.89
S3	Wall	740.7	28.70	25053.50	6263.38	5637.04	36953.92
	Roof	195.6	8.26				
	G.F.	168.9	12.91				
S4	Wall	740.7	52.96	47170.89	11792.72	10613.45	69577.07
	Roof	195.6	12.10				
	G.F.	168.9	33.00				

Cost per housing unit in Figure 4.42 indicates the amount of money that each family should pay for the actions. The third level of the wall and whole opaque system amendments (S2 & S4) charge owners with the very high budget. Shading device applications (S12-S13) together with solar collector application (S15), heated floor application (S16) and replacement of current air conditioner units by High-Efficiency ones with COP=4.0 (S21) also charge owners with a very high payment for actions. PV application (S22) is an expensive measure but can be divided into some steps with acceptable initial investment costs. Except seventh level of glazing system improvement (S11), all of the glazing system enhancements (S5-S11) have less than 2270TL investment cost while most of them require about 1000 TL. Modification of existing heating system by adding the variable heat pump (S14) and replacement of existing lamps with LED lights (S23) are the most cheaper measures. Other measures seem to have the reasonable amount of payment or can be applied by one-year postponement while items with more than 2270TL cost need to pay more attention (Figure 4.42).

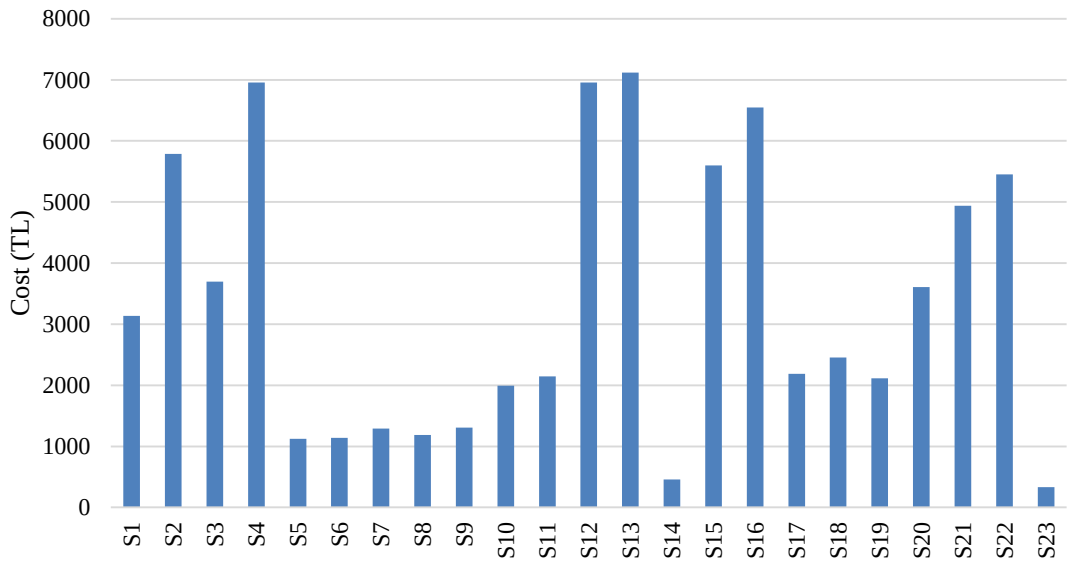

Figure 4.42 : Cost per Flat of Single Retrofit Measures (Row-Erzurum).

The payback period for each single measure is calculated to determine its feasibility. The modification of existing heating system by adding the variable heat pump (S14) and the replacement of the existing lamps with LED ones (S23), the replacement of existing combi-boiler with condensing one and central condensing/non-condensing boiler (S17-S19) by less than five-year periods are in the first rank while. From architectural improvement measures (S1-S13), opaque system enhancements (S1-S4)

have very high payback periods, just one of glazing system enhancements (S9) has less than ten years' payback time. The third and sixth level of glazing improvements (S8 & S10) have less than 15 years' payback period. PV application (S22) will pay back the investment cost to the owner in less than 15 years. Rest of the measures have a high payback period and are irrational to take to the account (Figure 4.43).

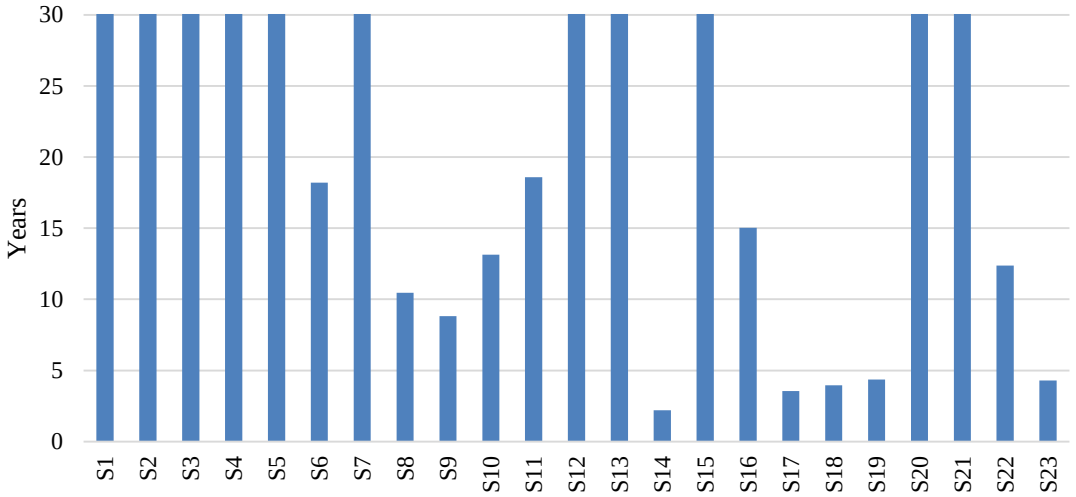

Figure 4.43 : The payback period of each single measure (Row-Erzurum).

Figure 4.44 shows the amount of CO_2 emission of each single measure in Erzurum's case. It is possible to reach to about 33% of CO_2 emission saving by replacement of existing combi-boiler by condensing combi-boiler or central boiler (S17-S18). The replacement of existing combi-boiler by the non-condensing central boiler (S19) together with heated floor application (S16) and application of PV system (S22) are also effective from CO_2 emission point of view. They can reduce more than 20% of yearly emission (Figure 4.44).

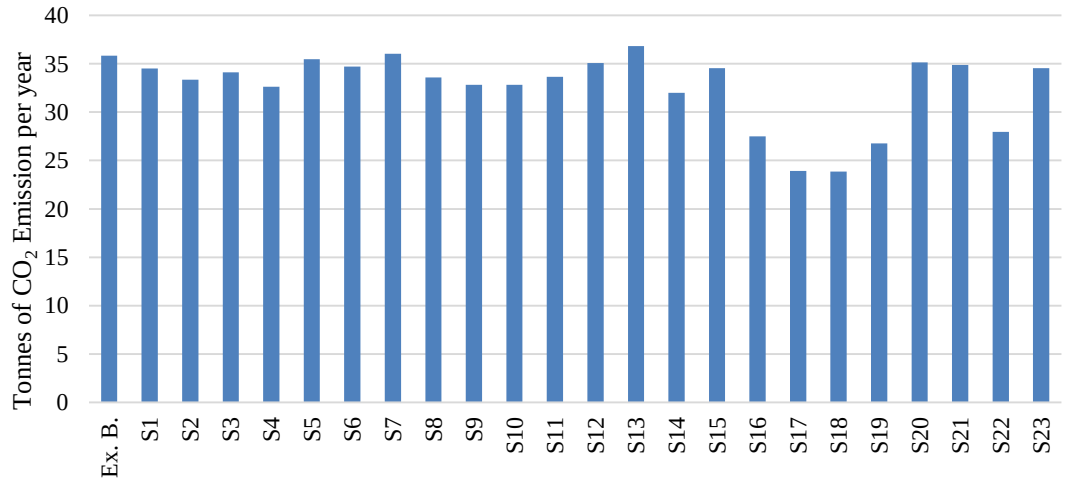

Figure 4.44 : CO_2 emission of each single measure (Row-Erzurum).

The existing case study building has approximately 570 TL/m^2 global cost. The replacement of existing combi-boiler by condensing central boiler (S18) with 424 TL/m^2 global cost and about 112 kWh/m^2 PEC is located at the lowest point of the graph. Most of the measures are located above case study building, hence, should be eliminated from further analyzes. Thus, opaque system improvements (S1-S4), First and third level of glazing system amendments (S5 &S7), shading system applications (S12-S13), solar collector application (S15), application of heated floor (S16) and improvements of existing cooling systems (S20-S21) had been excluded from analyzes. From rest of glazing system enhancements, sixth and seventh level (S10 & S11) have more global cost in compare with the fourth and fifth level of improvement, hence, should be eliminated from further analyzes. PV application (S22) is not reducing the global cost in a considerable amount but is reducing the PEC in a significant amount, hence, can be included in further analysis. More than a half of measures are excluded from further analyzes, so the number of required simulations are reduced significantly (Figure 4.45).

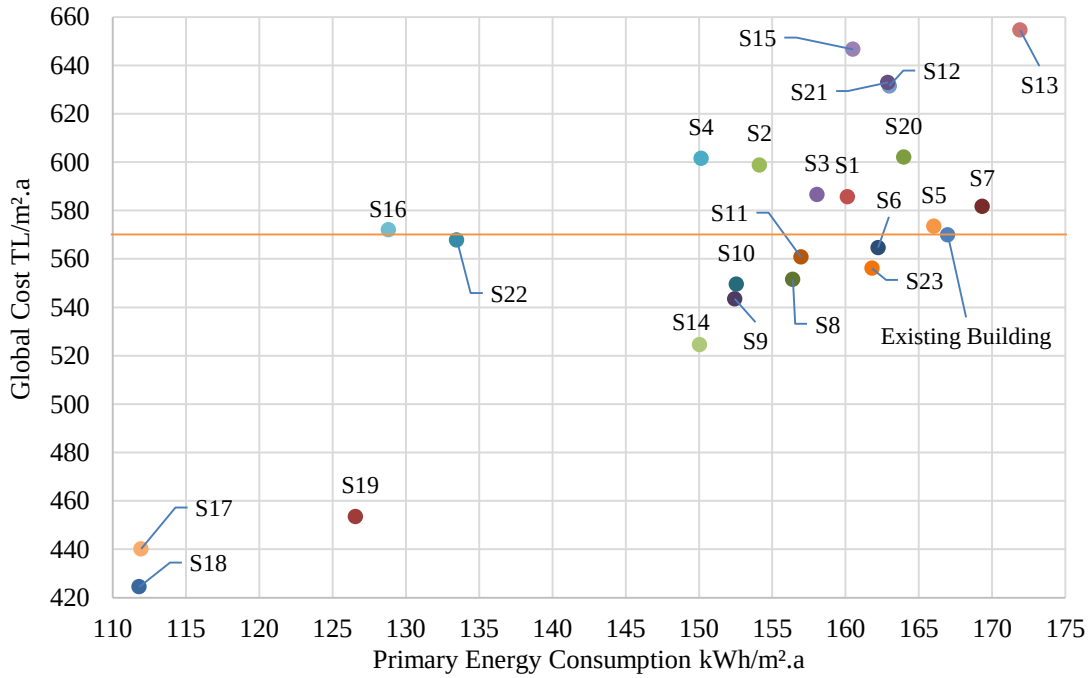

Figure 4.45 : The global cost vs. primary energy consumption graph for single measures (Row-Erzurum).

Rest of the single measures combined to define the retrofit packages. Similar to previous cases, to reduce the number of simulations, first of all, architectural and mechanical system combination are identified and analyzed. From architectural and

mechanical combination measures, three scenarios are ERCMs. The characteristics of these ERCMs are indicated in Table 4.33. In general, when proper glazing system improvements (S6 & S8-S9) combined with existing combi-boiler replacement by central condensing boiler (S18), the retrofit will be located in the lowest area of the related graph from a global cost point of view. Moreover, ERCMs can reduce global cost by approximately 27% and PEC by about 37% (Figure 4.46 and Table 4.33).

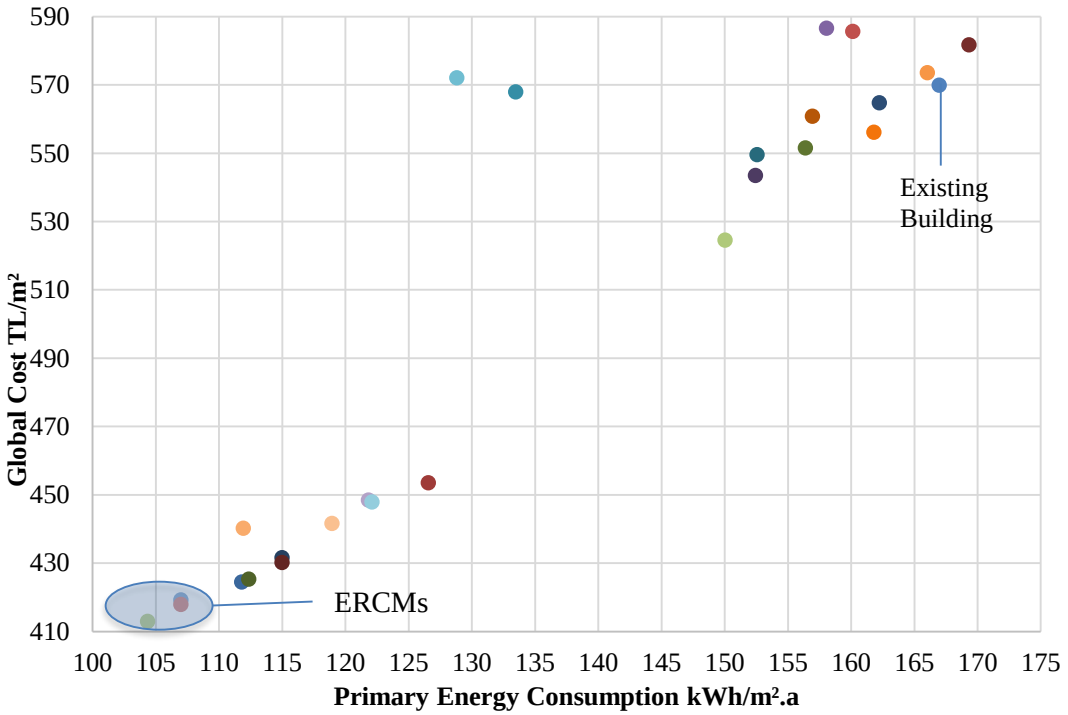

Figure 4.46 : The global cost vs. primary energy consumption graph for combination of the architectural and mechanical measures (Row-Erzurum).

Table 4.33 : Energy efficiency measures that constitute the ERCMs (Row-Erzurum).

Acr.	Energy Efficiency Measure (Architecture)	Energy Efficiency Measure (HVAC System)
P7	2th Glazing (S6)	Condensing Central Boiler (S18)
P8	4th Glazing (S8)	Condensing Central Boiler (S18)
P9	5th Glazing (S9)	Condensing Central Boiler (S18)

Then, lighting system improvements and after that PV applications are applied to the ERCMs. Similar analyzes are done for related combined measures, and the necessary global cost vs. primary energy consumption graph is provided for these actions. By application of lighting system amendment and PV system to the ERCMs, it is possible to reach to about 400 TL/m^2 global cost and approximately 67 kWh/m^2 PEC. The global cost amount of the scenarios including PV system and lighting system's

improvement are the same with scenarios including just lighting system's improvement. It means that global cost losses and benefits of PV system addition are equal. Though, the PEC amount of packages with PV system application are significantly lower than just LED application. Thus, packages with PV and LED application should be chosen as cost-optimal scenarios. So, the cost-optimal scenarios can provide about 60% PEC saving together with 30% global cost saving for the existing building (Figure 4.47).

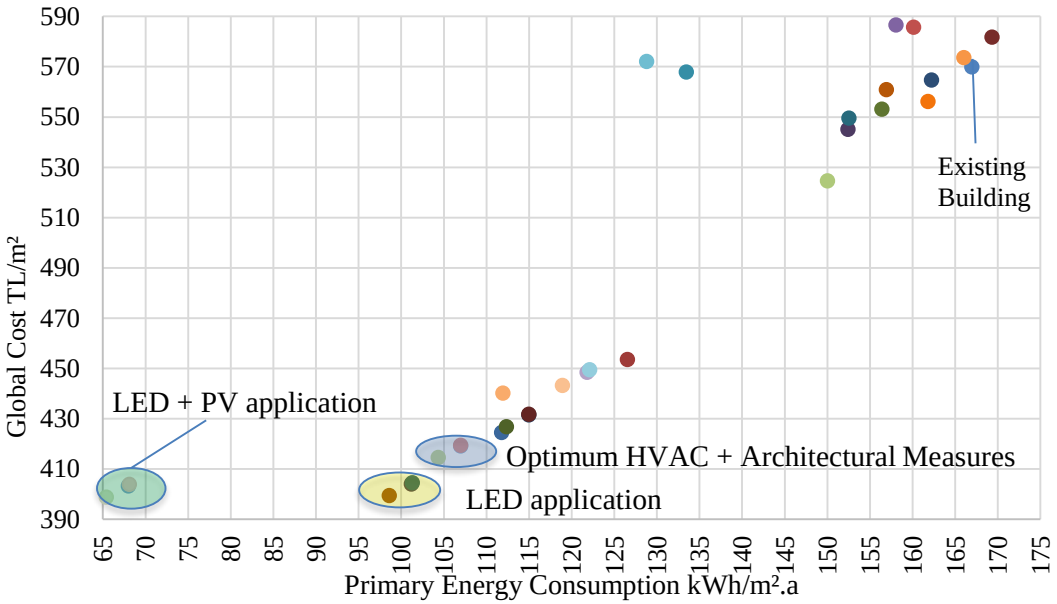

Figure 4.47 : The global cost vs. primary energy consumption graph for whole scenarios (Row-Erzurum).

The initial investment cost and cost per flat of the cost-optimum scenarios are indicated in Table 4.34. As seen there, the contribution amount for each owner in all cases is more than the payable amount. Thus, all of them should be analyzed to apply as step-by-step retrofits. All optimum scenarios have about/less than eight years' payback period. (Table 4.34).

Table 4.34 : Cost per flat and payback time for cost optimum scenarios (Row-Erzurum).

	Total Initial Investment Cost (TL)	Cost per Flat (TL)	Payback Period (yr.)
P7+LED+PV	93,762.61	9,376.26	7.80
P8+LED+PV	95,796.47	9,579.65	7.93
P9+LED+PV	96,996.38	9,699.64	7.88

4.5.2.3 Results of energy-cost analyses for the row building located in Istanbul

Based on Table 4.9, a set of retrofit measures were created to apply to the case study building in Istanbul. Table 4.35 is representing the amount of insulation layers that had been implemented to the case study building as the single retrofit measures (Table 4.35). For the glazing system, the descriptions available in Table 4.15 and for the energy systems, the descriptions identified in Table 4.9 are used.

Table 4.35 : Description of single retrofit measures of opaque components for row building in Istanbul.

Acr.	Values	Description
S1	U_{wall} = 0.43 W/m^2.K	3cm Insulation Layer- 0.035W/m.K
S2	U_{wall} = 0.29 W/m^2.K	7cm Insulation Layer- 0.035W/m.K
S3	U_{wall} = 0.43 W/m^2.K	3cm Insulation Layer- 0.035W/m.K
	U_{roof} = 0.28 W/m^2.K	4cm Insulation Layer- 0.04W/m.K
	U_{floor} = 0.43 W/m^2.K	3cm Insulation Layer- 0.035W/m.K
S4	U_{wall} = 0.29 W/m^2.K	7cm Insulation Layer- 0.035W/m.K
	U_{roof} = 0.19 W/m^2.K	10cm Insulation Layer- 0.04W/m.K
	U_{floor} = 0.29 W/m^2.K	6cm Insulation Layer- 0.035W/m.K

Similar to previous studies, first of all, the energy analyses had been done for single retrofit measures, then based on that analyzes, further analyzes have been done for combined measures. The energy consumption of each single retrofit measure is calculated and indicated in Figure 4.48. In general, the results show that heating system improvements (S14-S19) and PV system addition (S22) are more efficient than other enhancements. Among improvement scenarios for the heating system, replacement of current combi-boiler with central condensing boiler (S18) is the best one and can reduce PEC by more about 27% to reach to 102.7 kWh/m^2.a. The potential of PEC reduction in cooling system improvement's scenarios (S20-S21) is just 7.5%. Lighting system improvement (S25) reduces the PEC by approximately 4%. From architectural improvements (S1-S13), glazing system retrofits (S5-S11) are most efficient measures. They can decrease more than 10% of PEC. Opaque system enhancements (S1-S4) can reduce just 7.5% of whole PEC at most. Shading device application (S12-S13) can improve PEC by just 3% (Figure 4.48).

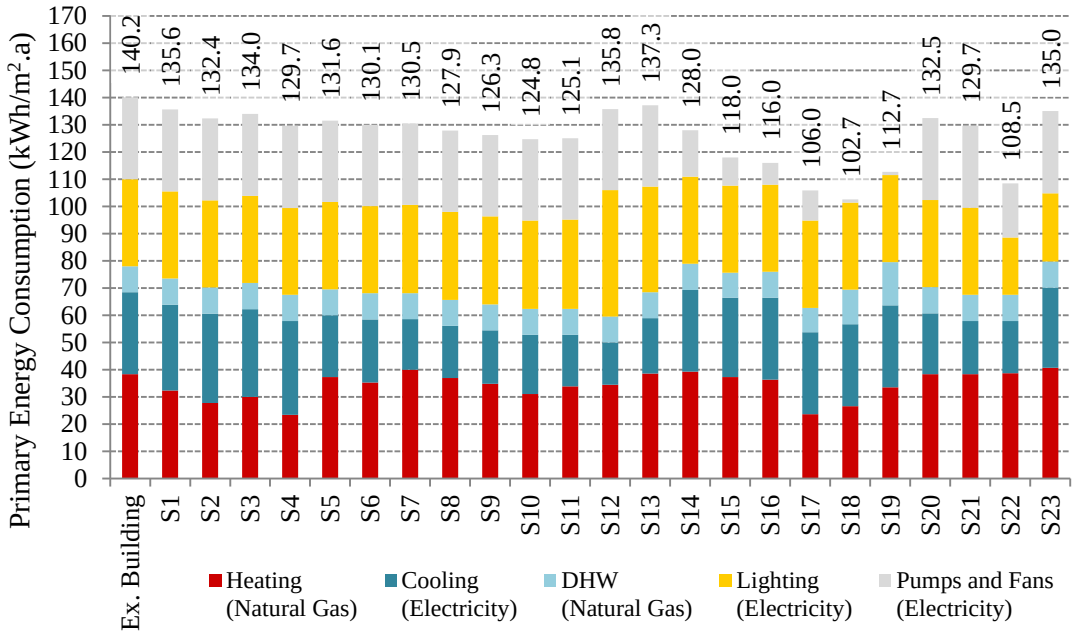

Figure 4.48 : Yearly PEC of each single measure of row building in Istanbul.

The initial investment costs for opaque system improvement are illustrated in Table 4.36. When available, costs from three material producer are provided as unit price for each measure. In roof and floor retrofits, the cost of extra materials is added to unit costs as a constant value (Table 4.36). For rest of measures values indicated in Table 4.28 are used as the same measures are applied in Istanbul and Antalya. The related cost of combined measures is calculated based on these tables as well.

Table 4.36 : Cost calculations for opaque system improvements of the row building in Istanbul.

Acr.	Improved Component	Amount (m2 / piece)	Average unit Cost (TL)	Material Cost (TL)	Indirect Cost (TL)	TAX (TL)	Total Cost (TL)
S1	Wall	740.7	24.11	17860.01	4465.00	4018.50	26343.51
S2	Wall	740.7	33.51	24820.36	6205.09	5584.58	36610.04
S3	Wall	740.7	24.11	21914.80	5478.70	4930.83	32324.33
	Roof	195.6	13.48				
	G.F.	168.9	8.40				
S4	Wall	740.7	33.51	29206.53	7301.63	6571.47	43079.62
	Roof	195.6	5.85				
	G.F.	168.9	19.20				

Cost per housing unit in Figure 4.49 indicates the amount of money that each family should pay for each action. Shading device applications (S12-S13) together with a solar collector (S15) and heated floor application (S16) provide owners with a very high payment for actions. PV application (S22) and replacement of the existing air conditioner units by high-efficiency one with COP=4.0 (S21) also cost too much for the owner. From these measures, just PV application can be divided to some sub-measures that cost properly for owners. Modification of existing heating system by adding the variable heat pump (S14) and replacement of existing lamps with LED lights (S23) are the most cheaper measures. Other measures seem to have the reasonable amount of payment while items with more than 2270TL cost need to pay more attention (Figure 4.49).

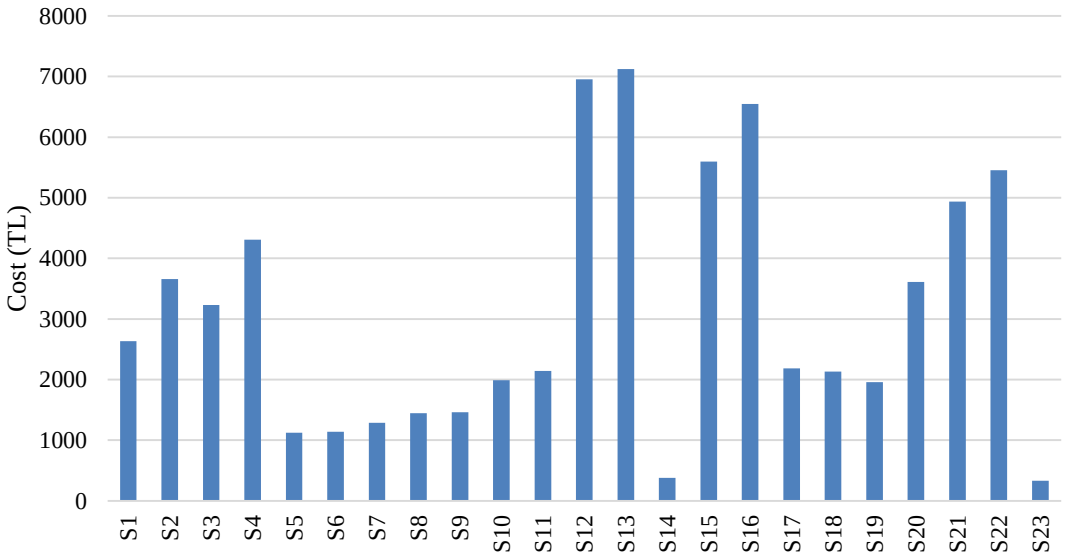

Figure 4.49 : Cost per flat of single retrofit measures (Row-Istanbul).

The payback period for each single measure is calculated to determine its feasibility. The modification of existing heating system by adding the variable heat pump (S14) and the replacement of the existing lamps with LED ones (S23) and the replacement of existing combi-boiler by central condensing boiler (S18) by less than five-year periods are in the first rank while replacement of existing combi-boiler by condensing combi boiler (S17) and central non-condensing boiler (S19) by duration of about five years are following them. From architectural improvement measures (S1-S13), opaque system enhancements (S1-S4) and shading elements applications (S12-S13) have very high payback periods. Most of the glazing system improvements (S5-S11) have approximately ten years' payback time. PV application (S22) and solar collector

addition to the heating system (S15) will pay back the investment costs to the owner in less than 15 years. Rest of the measures have a high payback period and are irrational to take to the account (Figure 4.50).

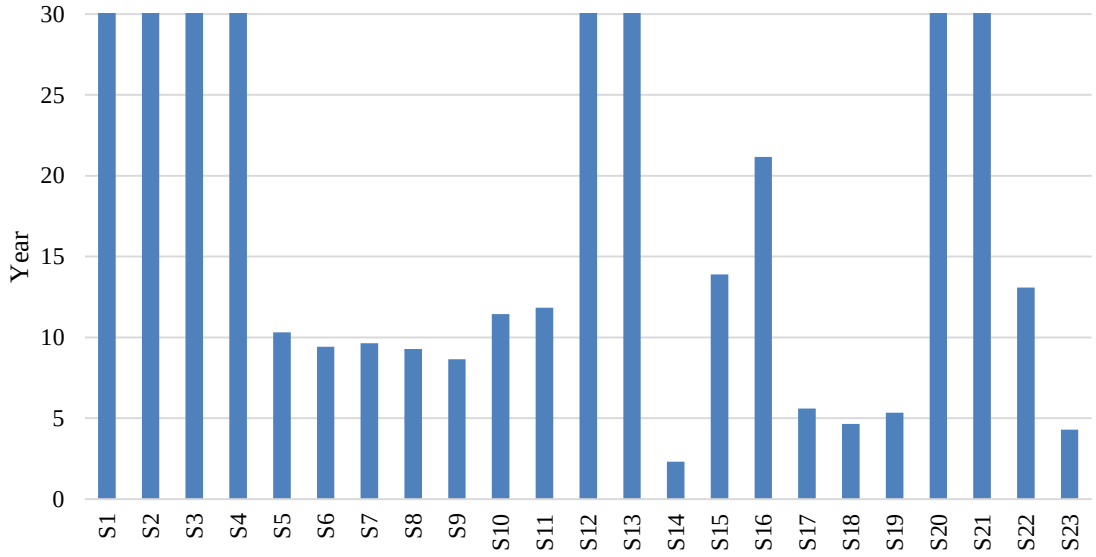

Figure 4.50 : The payback period of each single measure (Row-Istanbul).

Figure 4.51 shows the amount of CO_2 emission of each single measure. It is possible to reach to about 27% of CO_2 emission saving by application of S18 that is the replacement of the existing combi-boiler by condensing central boiler system. PV application (S22) provide 24% CO_2 emission reduction. About 9 actions can provide more than 10% CO_2 emission saving (Figure 4.51).

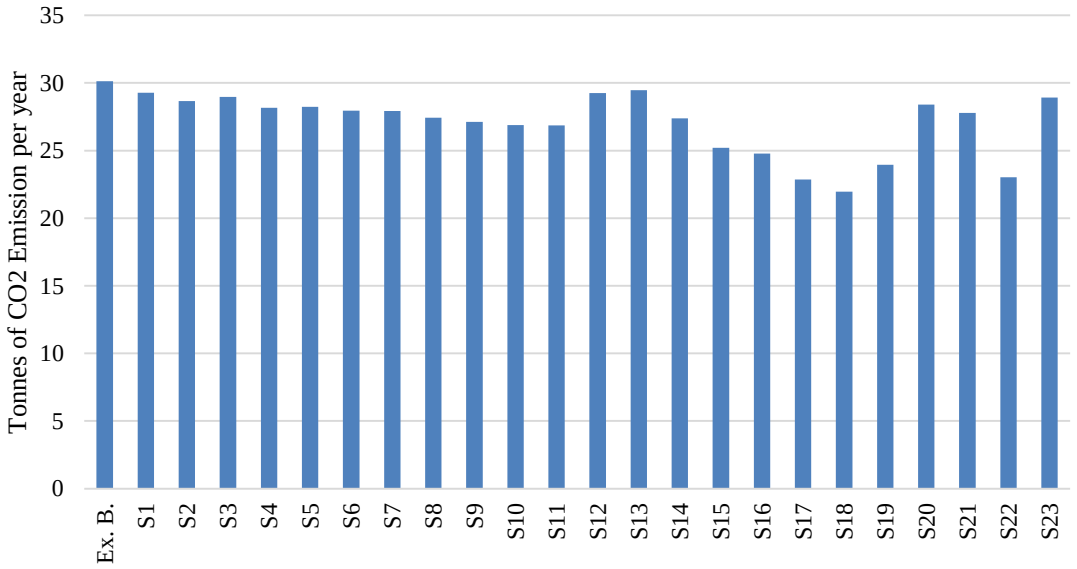

Figure 4.51 : CO_2 emission of each single measure (Row-Istanbul).

The existing case study building has approximately 519.57 TL/m^2 global cost. Replacement of the existing combi-boiler by central condensing boiler (S18) with about 412 TL/m^2 global cost and 102 kWh/m^2 PEC is located at the lowest point of the graph. Ten measures are located above case study building, hence, should be eliminated from further analyzes. Thus, opaque system improvements (S1-S4), shading system applications (S12-S13) and cooling system enhancements (S20-21) together with solar collector addition to the heating system (S15) and application of heated floor (S16) had been excluded from further analyzes. From glazing system improvements, first, the second, third and fifth level of the amendment (S5-S9) are decreasing the amount of global cost and PEC of existing case study building. Sixth and seventh level of glass improvements (S10-S11) have located above the fifth level of improvement (S9), hence, will not lead to reaching the lowest point of the whole measures global cost vs. primary energy consumption graph and should be eliminated from further analyzes. S6 and S7 lead to very close results thus one of them should be omitted. Replacement of combi-boiler with central boiler (S18-S19) are more efficient than replacement with condensing combi-boiler (S17), so S17 should not be used in combinations. Thus, the number of required simulations is reduced significantly (Figure 4.52).

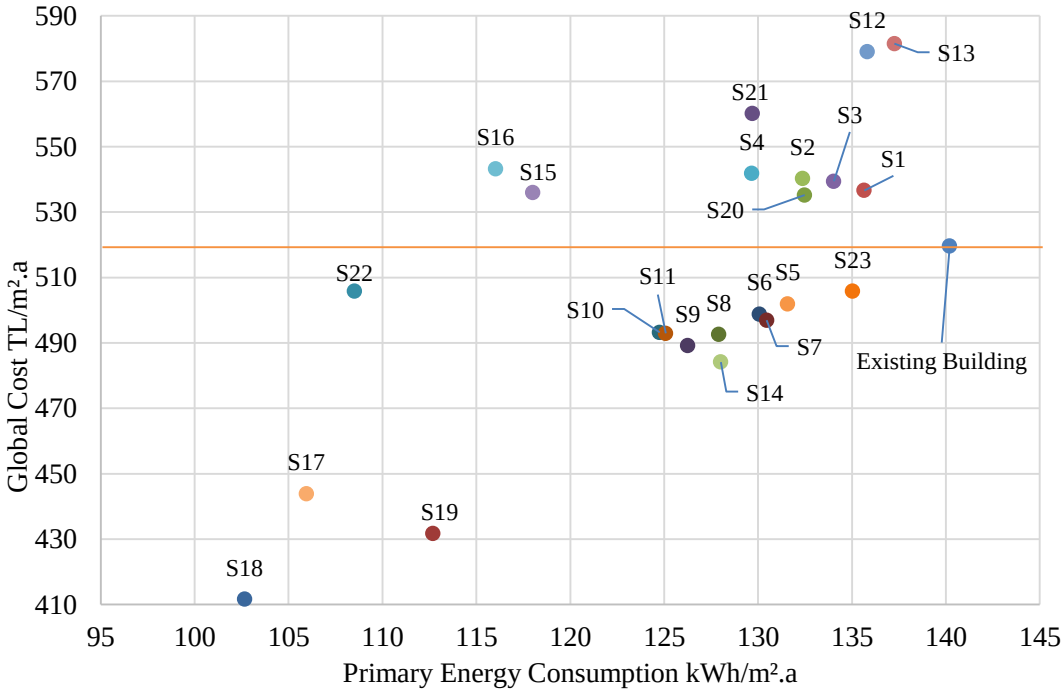

Figure 4.52 : The global cost vs. primary energy consumption graph for single measures (Row-Istanbul).

Rest of the single measures should be combined to define the retrofit packages. To reduce the number of simulations, first of all, architectural and mechanical system combination are identified and simulated. From architectural and mechanical combination measures, three scenarios are ERCMs which are located in the lowest area of the graph from a global cost point of view. The characteristics of the ERCMs are indicated in Table 4.37. In general, when proper glazing system improvements (S7-S9) combined with the existing combi-boiler replacement by central condensing boiler (S18), the retrofit will be economically reasonable. Moreover, ERCMs can reduce global cost by approximately 27% and PEC by about 37% (Figure 4.53 and Table 4.37).

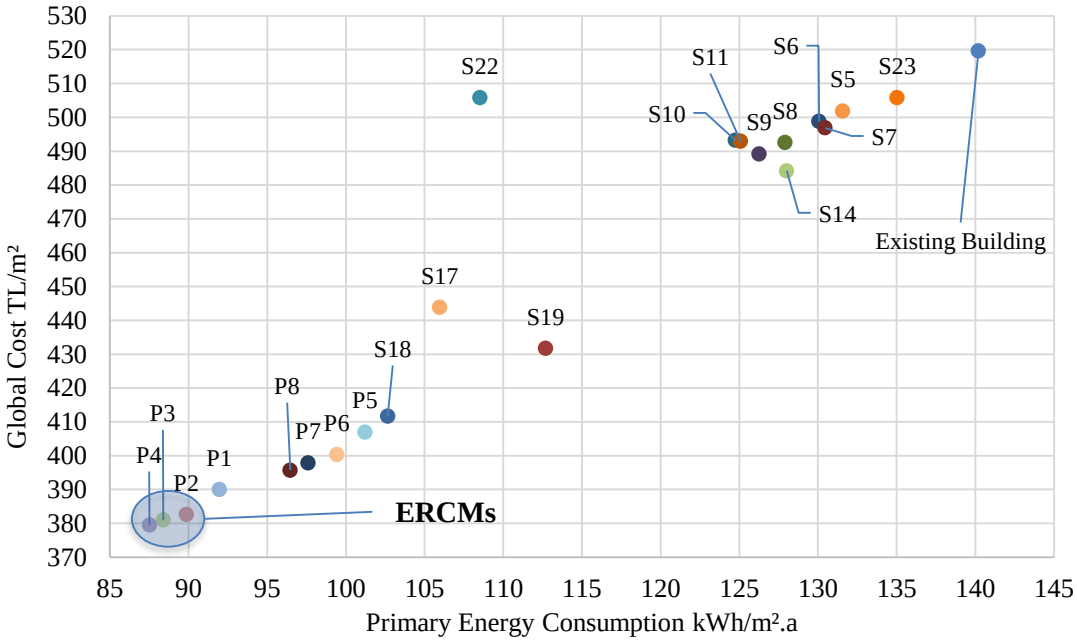

Figure 4.53 : The global cost vs. primary energy consumption graph for the combination of architectural and mechanical measures (Row-Istanbul).

Table 4.37 : Energy efficiency measures that constitute the ERCMs (Row-Istanbul).

Acr.	Energy Efficiency Measure (Architecture)	Energy Efficiency Measure (HVAC System)
P2	3th Glazing (S7)	Central Condensing Boiler (S18)
P3	4th Glazing (S8)	Central Condensing Boiler (S18)
P4	5th Glazing (S9)	Central Condensing Boiler (S18)

Then, lighting system improvements and after that PV applications are applied to the ERCMs. Similar analyzes are done for related combined measures, and necessary global cost vs. primary energy consumption graph is provided for these actions. By

application of lighting system amendment and PV system to the ERCMs, it is possible to reach to about 345 TL/m^2 global cost and approximately 52 kWh/m^2 PEC. As these points are the lowest point of the related graph from a global cost point of view, the combination of ERCMs with lighting system improvement and PV system application are cost optimal scenarios. Thus, the cost-optimal scenarios can provide about 63% primary energy saving together with 34% global cost saving for the case study building (Figure 4.54).

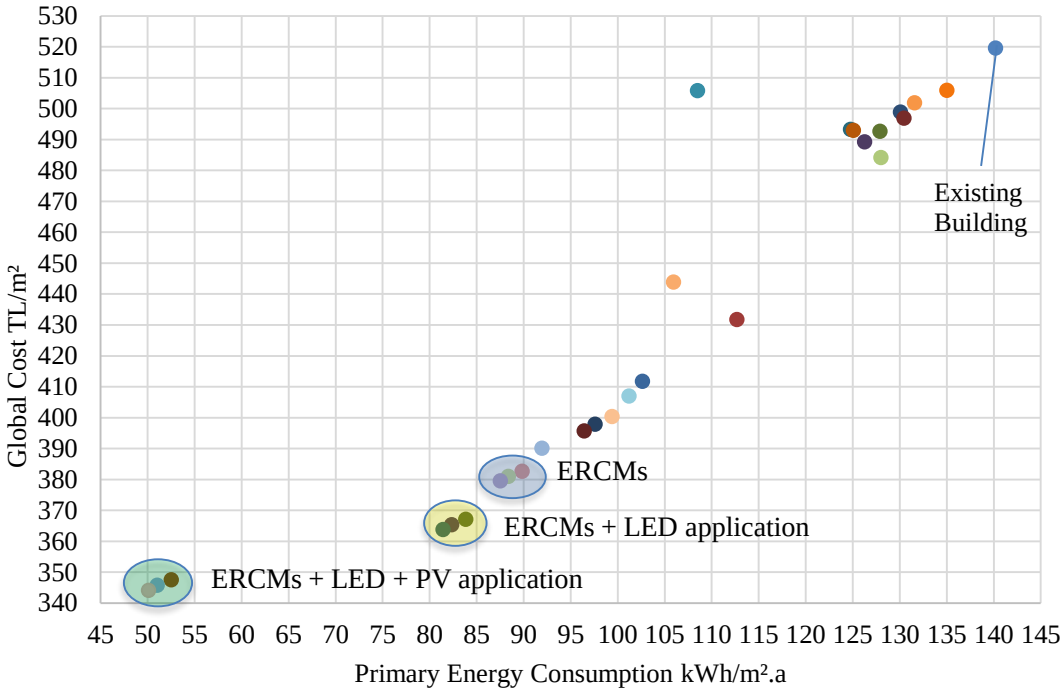

Figure 4.54 : The global cost vs. primary energy consumption graph for whole combined measures (Row-Istanbul).

The initial investment cost and cost per flat of the cost optimum scenarios are indicated in Table 4.38. As seen there, the contribution amount for each owner in all cases is more than the payable amount. Thus, all of them should be analyzed to apply as step-by-step retrofits. All optimum scenarios have less than nine years' payback period. (Table 4.38)

Table 4.38 : Cost per flat and payback period for cost optimum scenarios (Row-Istanbul).

	Total Initial Investment Cost (TL)	Cost per Flat (TL)	Payback Period (yr.)
P2+LED+PV	93040.19	9304.01	8.34
P3+LED+PV	94588.08	9458.80	8.39
P4+LED+PV	94768.06	9476.80	8.35

4.6 Determination of Proper Step-By-Step Retrofit Scenarios and Carry Out Related Energy-Cost Analyses for the Case Study Residential Buildings

After determination of cost-optimal measures, it is time to make them applicable in large-scale. To make any scenario applicable on a large scale, it is necessary to have an enormous financial support that is unattainable without owners' contribution especially for the country like Turkey. Based on the result of the current study, the amounts of money that are required for application of cost-optimal measures are approximately between 9000 and 15000 TL. This amount is about a half of household income in 2015. Hence, it is unreasonable to apply them as one step actions. It is evident that compare to the instant application, the amount of energy benefits raised from the step-by-step application of proper retrofit actions would be lower. On the contrary, the rate of retrofit actions in the large scale would be increased significantly so that it can provide a huge benefit for the country.

The first step to determine whether the step-by-step application is reasonable or not, is to define the proper scenario for the application. The number of possible combinations is too high, for example, there are 96 possible combinations to apply for a step-by-step scenario with five steps. In this study, just two different scenarios that seem rational are going to study for the step-by-step application. The first scenario is based on the amount of money that each flat's owner should pay for their action, so, starts with the measure containing the lowest cost for owners and finished with the measure require the highest cost among steps. The second scenario is based on the primary energy saving of each measure, so starts with the most primary energy saver single measure and last with the least energy saver single improvement. Yearly payment for each owner is fixed to 2270 TL. Each action that has less than 2270 TL cost for each flat owner will be applied in without any postponement. While the division to some steps would implement to the measures with about 2270 to 4540 TL cost, when it is possible, or with the one-year postponement. PV application that costs between 5100 and 5400 TL for each owner would be considered to apply in three steps.

4.6.1 Detached Buildings

The result of analyses related to the step-by-step retrofit of detached buildings located in the related representative cities are indicated in the followings:

4.6.1.2 Step-by-step retrofit analyses for the detached building in Antalya

Based on the methodology of the research, two step-by-step scenarios for the building were established. Some scenarios include an additional improvement in the heating system. Thus, three scenarios (P82+LED+PV, P83+LED+PV, and P84+LED+PV) should have six steps (Table 4.39) while the rest of the scenarios include seven steps (Table 4.40).

Table 4.39 : Definition of phases for step-by-step scenarios with six steps (Detached-Antalya).

Step No.	Scenario 1 Improvements	Application year	Cost per Flat (TL)	Step No.	Scenario 2 Improvements	Application year	Cost per Flat (TL)
1	Glazing and lighting system	0	2200-2500	**1**	1/3 of PV system	0	1679.9
2	Cooling system	2	3608.74	**2**	1/3 of PV system	1	1679.9
3	Opaque system	4	4143.06	**3**	1/3 of PV system	2	1679.9
4	1/3 of PV system	5	1679.9	**4**	Opaque system	4	4143.06
5	1/3 of PV system	6	1679.9	**5**	Cooling system	6	3608.74
6	1/3 of PV system	7	1679.9	**6**	Glazing and lighting system	7	2200-2500

Table 4.40 : Definition of phases for step-by-step scenarios with seven steps (Detached-Antalya).

Step No.	Scenario 1 Improvements	Application year	Cost per Flat (TL)	Step No.	Scenario 2 Improvements	Application year	Cost per Flat (TL)
1	Heating and lighting system	0	967.02	**1**	1/3 of PV system	0	1679.9
2	Glazing system	1	1800-2000	**2**	1/3 of PV system	1	1679.9
3	Cooling system	2	3608.74	**3**	1/3 of PV system	2	1679.9
4	Opaque system	4	4143.06	**4**	Opaque system	4	4143.06
5	1/3 of PV system	5	1679.9	**5**	Cooling system	6	3608.74
6	1/3 of PV system	6	1679.9	**6**	Glazing system	1	1800-2000
7	1/3 of PV system	7	1679.9	**7**	Heating and lighting system	0	967.02

Figure 4.55 and 4.56 are indicating the amount of PEC of each step during defined step-by-step scenarios (Figure 4.55 and Figure 4.56).

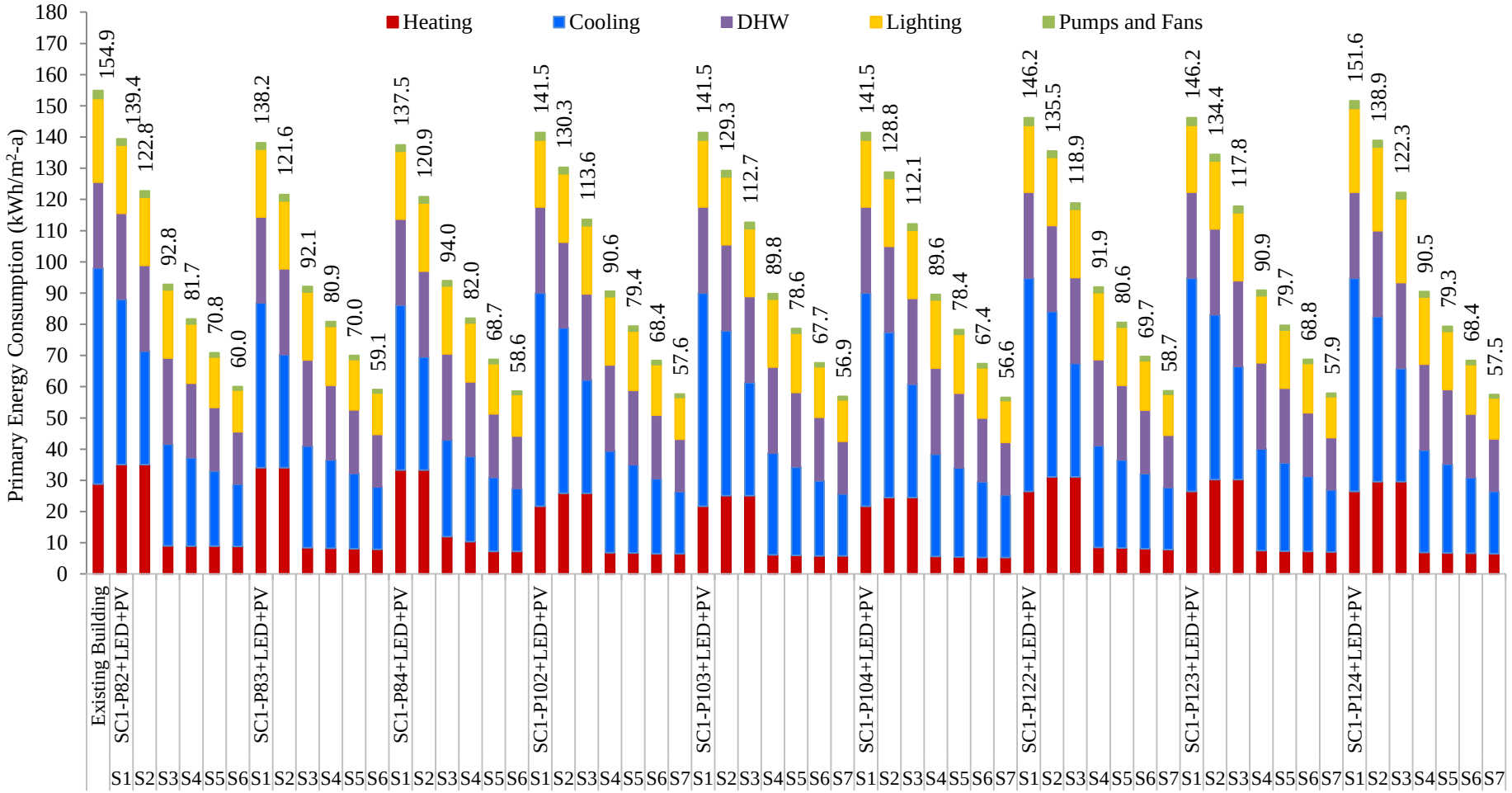

Figure 4.55 : PEC of each step during the first scenario application (Detached-Antalya).

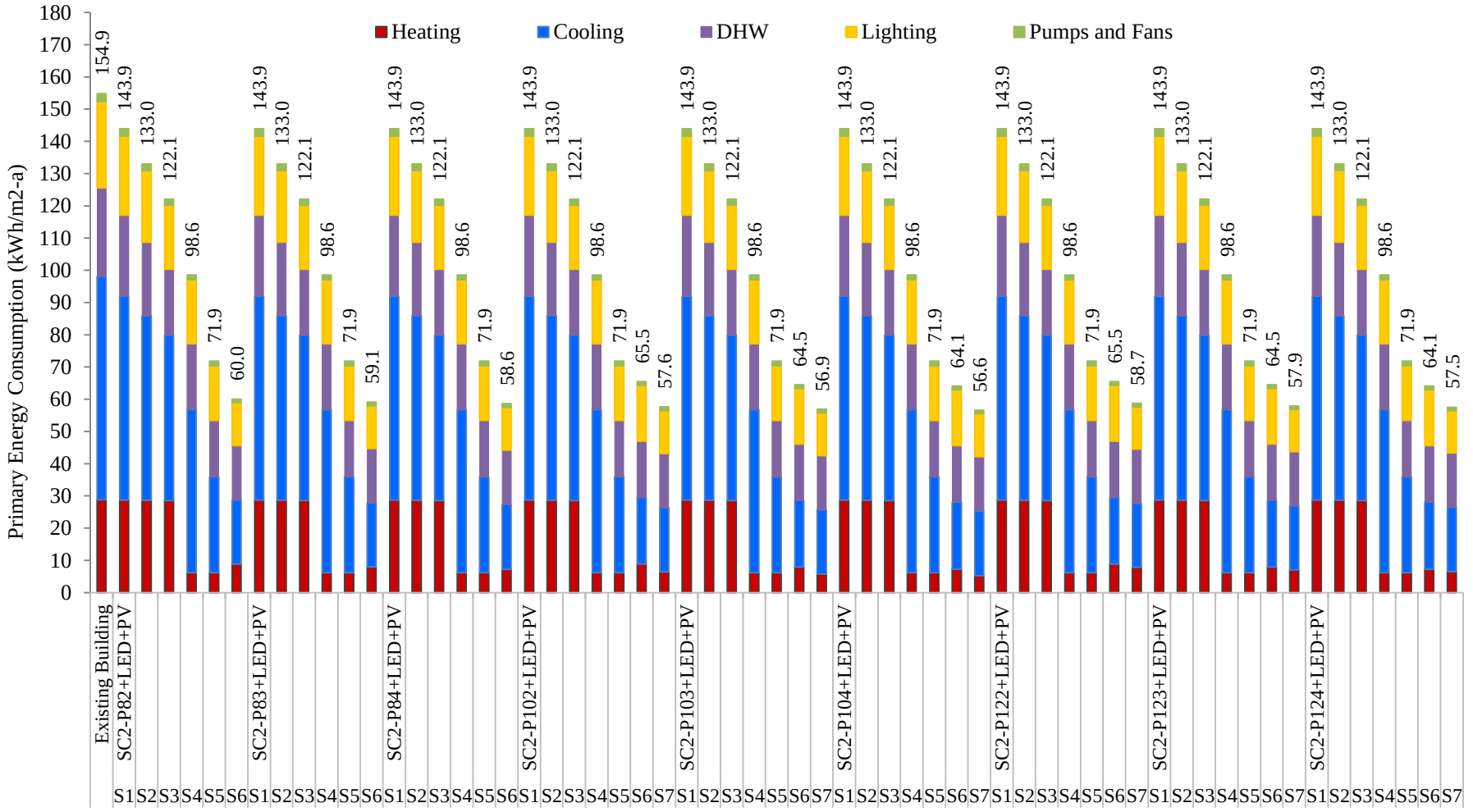

Figure 4.56 : PEC of each step during the second scenario application (Detached-Antalya).

The cost of each phase is calculated and defined based on the method that is defined in section 3.5. There is a little difference between global cost and PEC of the defined two scenarios. In general, all scenarios have about 70 kWh/m^2 average PEC during calculation period and 410-420 TL/m^2 global cost. The position of these scenarios in the global cost vs. primary energy consumption graph is indicating that compare with cost optimal retrofit scenarios; step-by-step scenarios have just 5% increase in global cost during the calculation period and approximately 17% grow in PEC. This amount is slight when to compare with the amount of step-by-step scenarios' global cost and PEC saving that are 28% and 55% respectively (Figure 4.57).

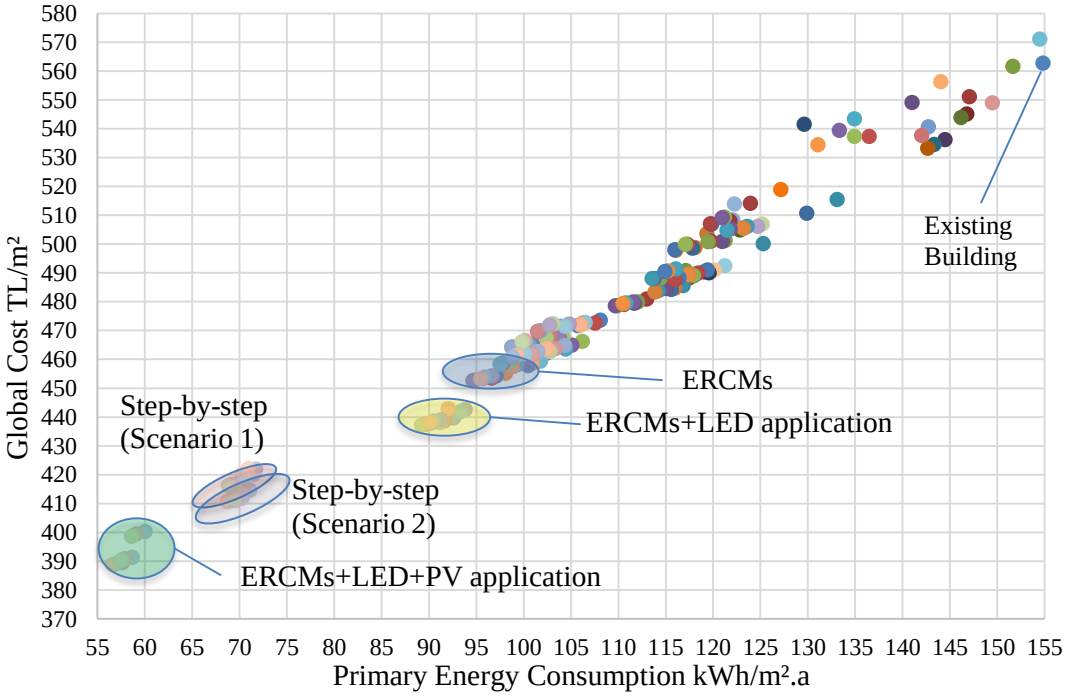

Figure 4.57 : The global cost vs. primary energy consumption graph for one step and step-by-step applications (Detached-Antalya).

4.6.1.2 Step-by-step retrofit analyses for the detached building located in Erzurum

As the cost per flat of opaque system improvements in this building is more that reasonable amount, the opaque system improvements are divided to two steps. One of them is exterior wall enhancement, and the other one is roof and ground floor upgrade. Thus, a scenario (P18+LED+PV) that contains just wall system improvement rather than whole opaque system improvement should include six steps (Table 4.41) while the rest of the scenarios should include seven steps (Table 4.42). One-year

postponement should apply to the wall and glazing system amendments due to the high cost per flat.

Table 4.41 : Definition of phases for step-by-step scenarios with six steps (Detached-Erzurum).

Step No.	Scenario 1 Improvements	Application year	Cost per Flat (TL)	Step No.	Scenario 2 Improvements	Application year	Cost per Flat (TL)
1	Heating and lighting system	0	967.36	**1**	Wall	1	4340.69
2	Glazing system	2	2742.32	**2**	Heating and lighting system	1	967.36
3	Wall	4	4340.69	**3**	1/3 of PV system	2	1679.9
4	1/3 of PV system	5	1679.9	**4**	1/3 of PV system	4	1679.9
5	1/3 of PV system	6	1679.9	**5**	1/3 of PV system	6	1679.9
6	1/3 of PV system	7	1679.9	**6**	Glazing system	7	2742.32

Table 4.42 : Definition of phases for step-by-step scenarios with seven steps (Detached-Erzurum).

Step No.	Scenario 1 Improvements	Application year	Cost per Flat (TL)	Step No.	Scenario 2 Improvements	Application year	Cost per Flat (TL)
1	Heating and lighting system	0	967.36	**1**	Ground floor and roof	0	969.74 - 1447.63
2	Glazing system	1-2	1566.92 -2742.32	**2**	Wall	2	3623.31 -4340.69
3	Ground floor and roof	2-3	969.74 - 1447.63	**3**	Heating and lighting system	3	967.36
4	Wall	4-5	3623.31 - 4340.69	**4**	1/3 of PV system	4	1679.9
5	1/3 of PV system	5-6	1679.9	**5**	1/3 of PV system	5	1679.9
6	1/3 of PV system	6-7	1679.9	**6**	1/3 of PV system	6	1679.9
7	1/3 of PV system	7-8	1679.9	**7**	Glazing system	7-8	1566.92 -2742.32

Figure 4.58 and 4.59 are indicating the amount of PEC of each step during defined step-by-step scenarios (Figure 4.58 and Figure 4.59).

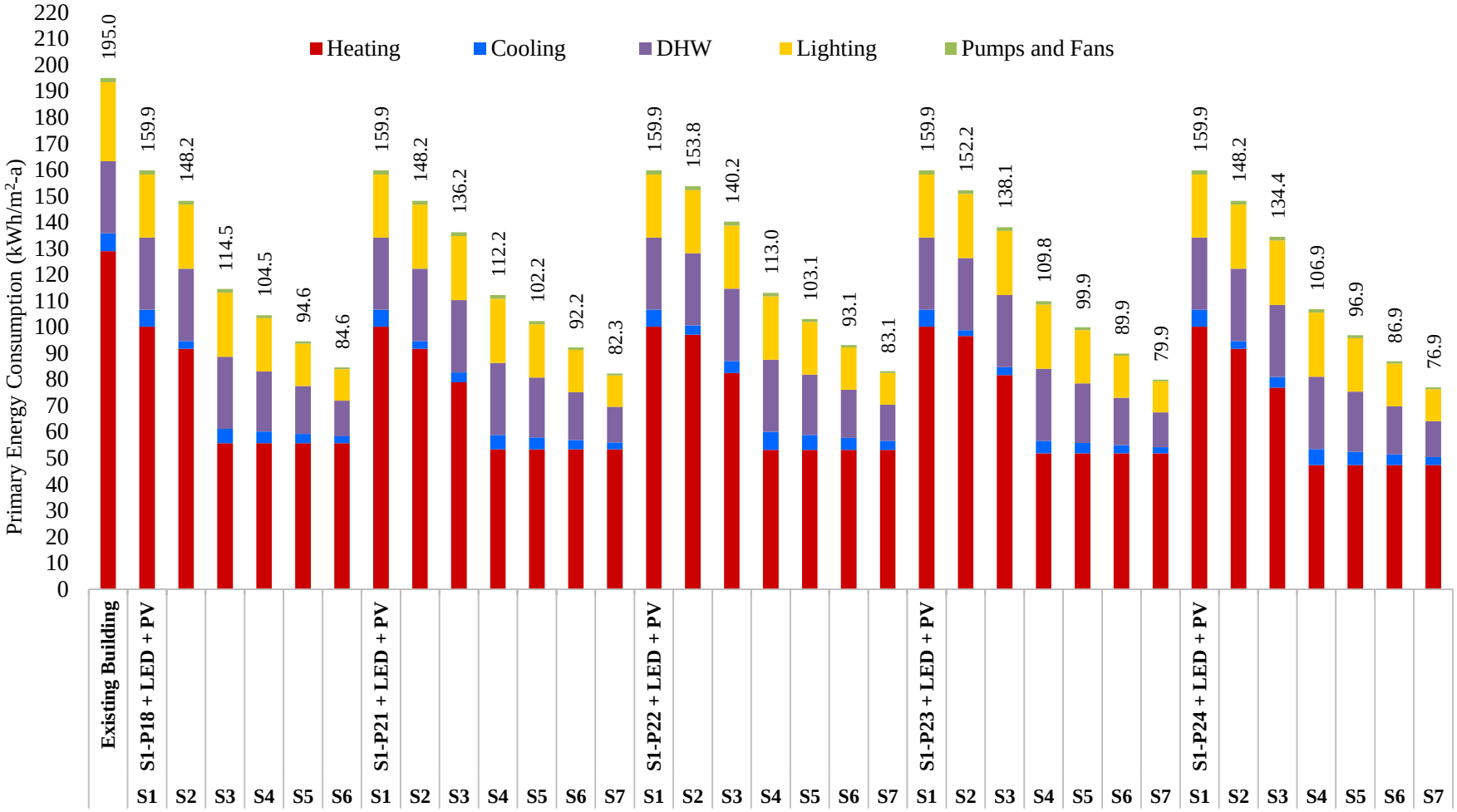

Figure 4.58 : PEC of each step with the first scenario application (Detached-Erzurum).

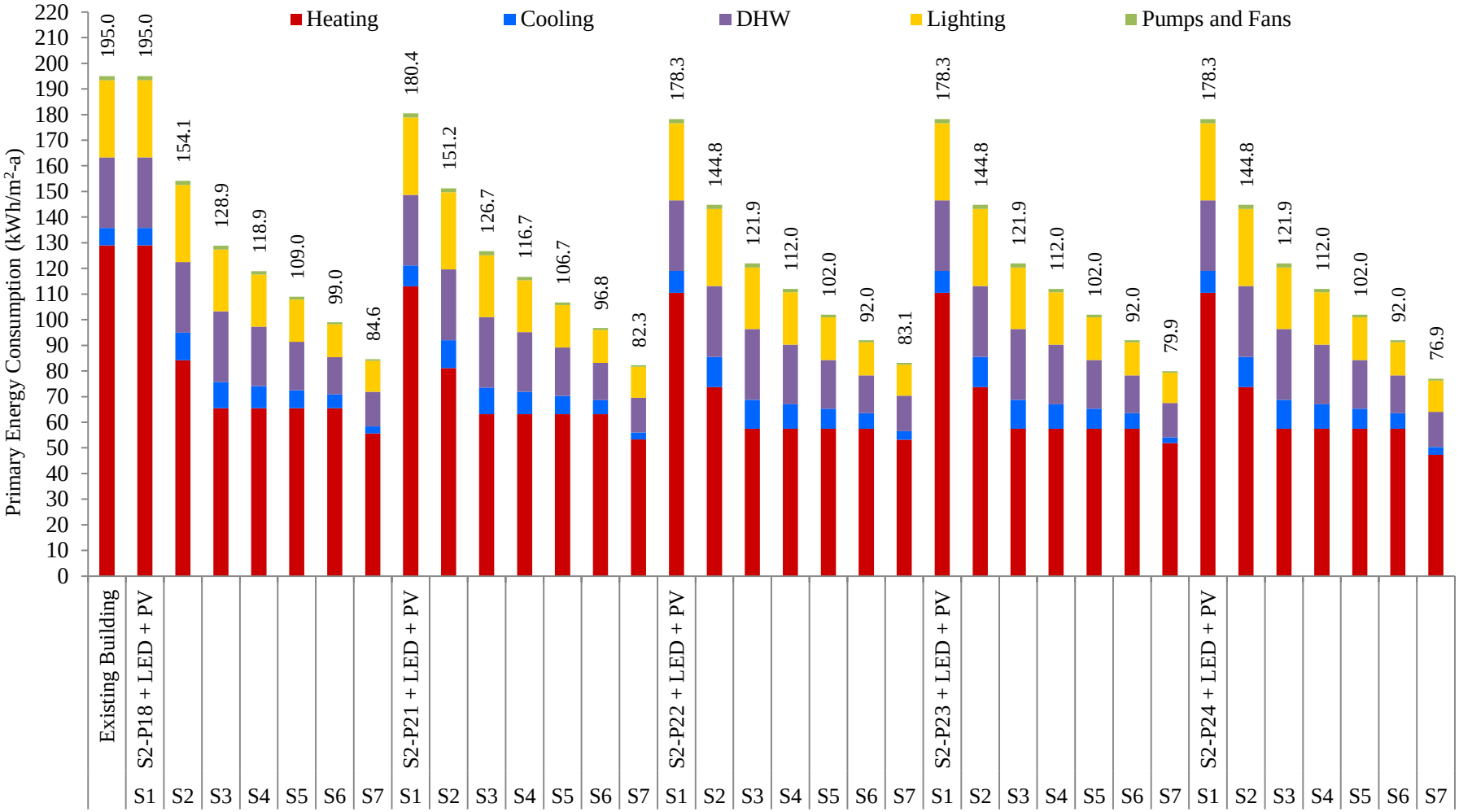

Figure 4.59 : PEC of each step with the second scenario application (Detached-Erzurum).

The cost of each phase is calculated and defined based on the methodology that is specified in section 3.5. There is a little difference between global cost and PEC of the defined two scenarios. In general, all scenarios have about 90-95 kWh/m^2 average PEC during calculation period and 415-430 TL/m^2 global cost. The position of these scenarios in the global cost vs. primary energy consumption graph is indicating that in comparison with optimum retrofit scenarios, step-by-step scenarios have just 2.5% increase in global cost during the calculation period and approximately 12% grow in PEC. This amount is negligible when to compare with the amount of step-by-step scenarios' global cost and PEC saving that are 30% and 52% respectively (Figure 4.60).

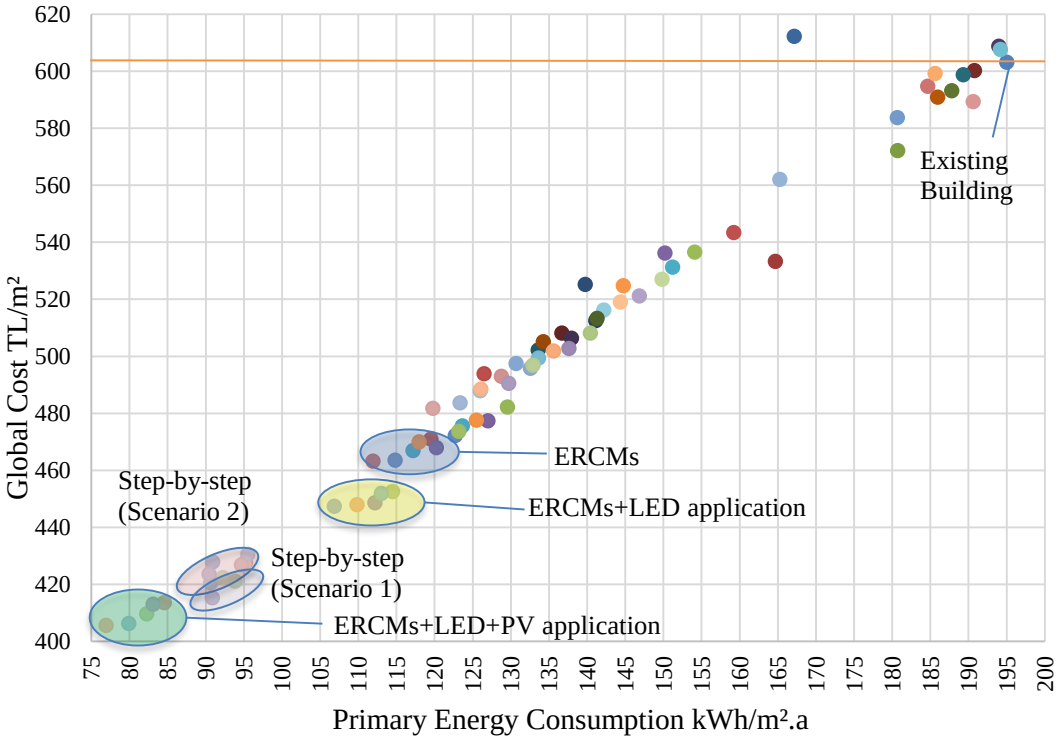

Figure 4.60 : The global cost vs. primary energy consumption graph for one step and step-by-step applications (Detached-Erzurum).

4.6.1.3 Step-by-step retrofit analyses for the detached building located in Istanbul

Based on the methodology of the research, all step-by-step scenarios for this building should include six steps. Wall and whole opaque amendments should be applied by the one-year postponement (Table 4.43).

Table 4.43 : Definition of phases for step-by-step scenarios (Detached-Istanbul).

Step No.	Scenario 1 Improvements	Application year	Cost per Flat (TL)	Step No.	Scenario 2 Improvements	Application year	Cost per Flat (TL)
1	Heating and lighting system	0	967.36	**1**	1/3 of PV system	0	1679.9
2	Glazing system	1	2012.14	**2**	1/3 of PV system	1	1679.9
3	Wall/whole opaque	3	3623.31-4767.81	**3**	1/3 of PV system	2	1679.9
4	1/3 of PV system	4	1679.9	**4**	Wall/whole opaque	4	3623.31-4767.81
5	1/3 of PV system	5	1679.9	**5**	Heating and lighting system	5	967.36
6	1/3 of PV system	6	1679.9	**6**	Glazing system	6	2012.14

Figure 4.61 is indicating the amount of PEC of each step during the defined step-by-step scenarios (Figure 4.61).

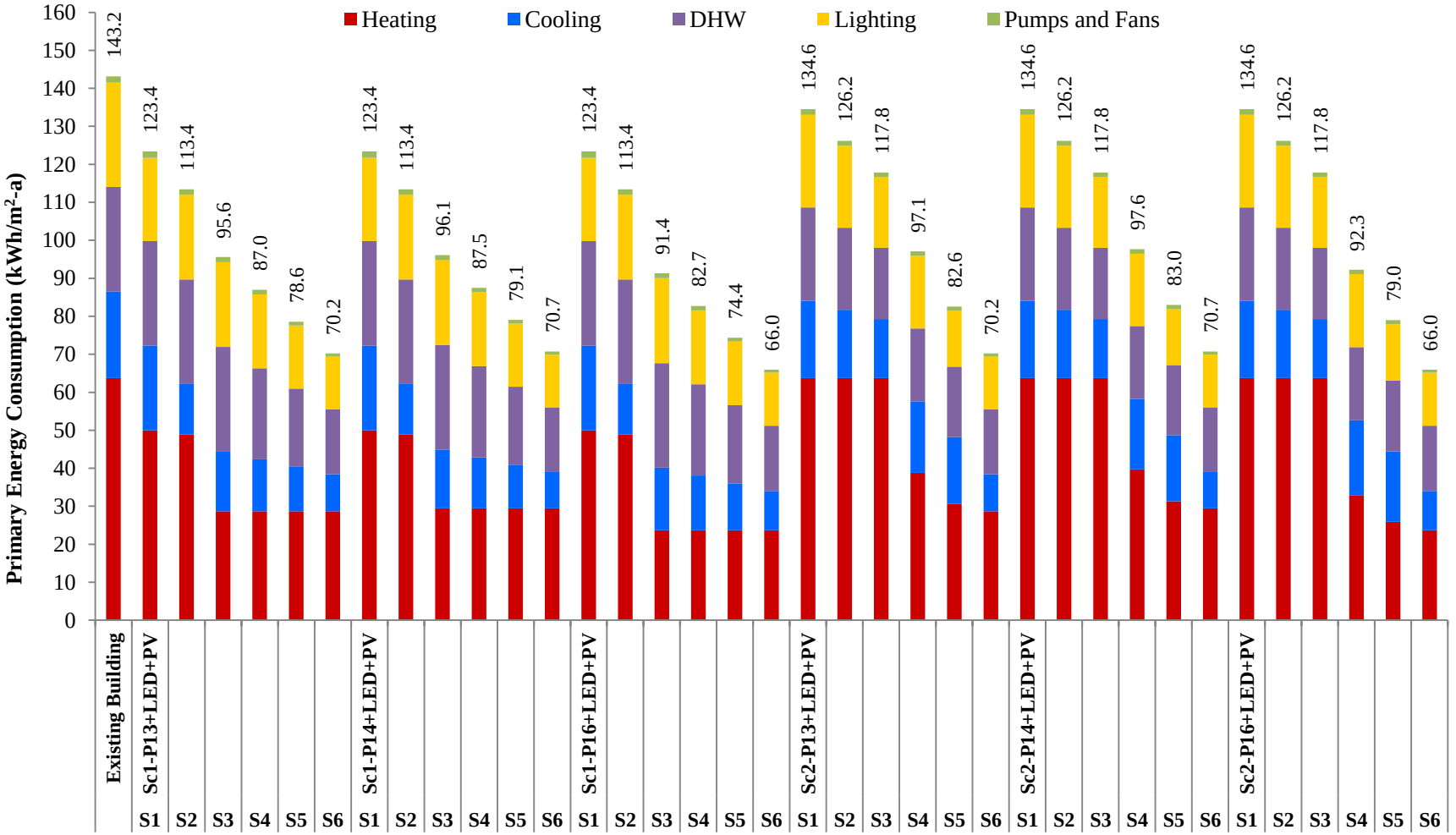

Figure 4.61 : PEC of each step with the first scenario application (Detached-Istanbul).

The cost of each phase is calculated and defined based on the method indicated in section 3.5. Similar to previous cases, there is a little difference between global cost and PEC of the defined two scenarios. In general, all scenarios have about 75-80 kWh/m^2 average PEC during calculation period and 385-395 TL/m^2 global cost. The position of these scenarios in the global cost vs. primary energy consumption graph is indicating that in comparison with optimum retrofit scenarios, step-by-step scenarios have just 2.5% increase in global cost during the calculation period and approximately 14% grow in PEC. This amount is negligible when to compare with the amount of step-by-step scenarios' global cost and PEC saving that are 21% and 47% respectively (Figure 4.62).

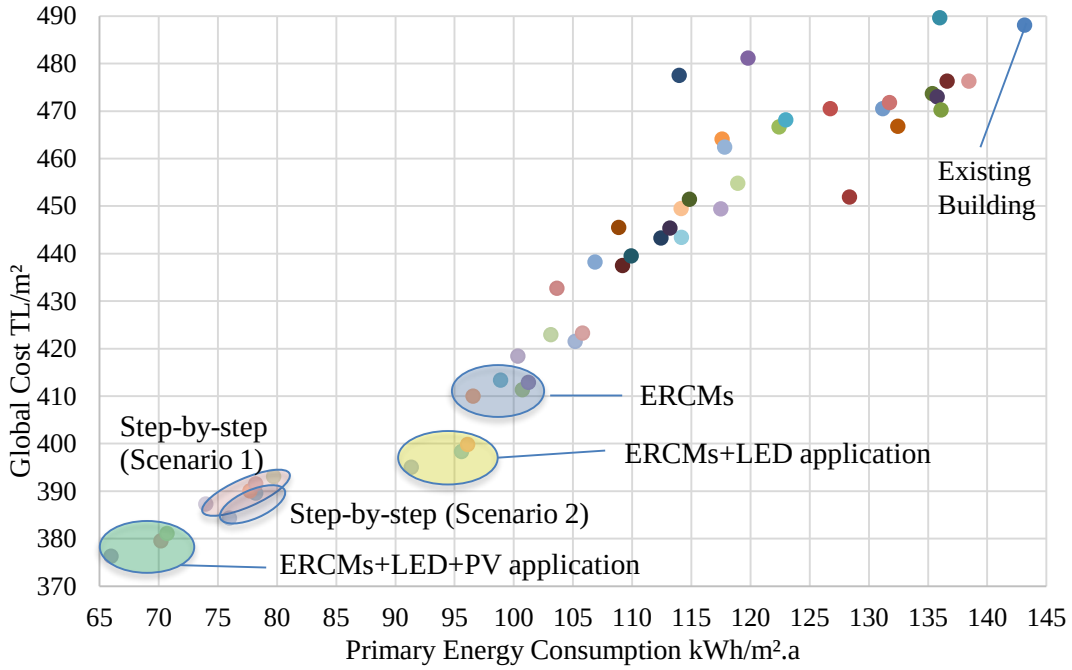

Figure 4.62 : The global cost vs. primary energy consumption graph for one step and step-by-step applications (Detached-Istanbul).

4.6.2 Row Buildings

Results of energy-cost analyses for the step-by-step retrofit of the row buildings are indicated in the followings:

4.6.2.1 Step-by-step retrofit analyses for the row building located in Antalya

In this building, the scenarios that don't contain cooling system improvements (P25+LED+PV, P26+LED+PV, and P27+LED+PV) have five steps (Table 4.44)

while the rest of the scenarios include six steps (Table 4.45). Heating and cooling systems' improvements should be applied by one-year postponements.

Table 4.44 : Definition of phases for step-by-step scenarios with five steps (Row-Antalya).

Step No.	Scenario 1 Improvements	Application year	Cost per Flat (TL)	Step No.	Scenario 2 Improvements	Application year	Cost per Flat (TL)
1	Glazing and lighting system	0	1620-1790	**1**	1/3 of PV system	0	1817.2
2	Heating system	2	2456.54	**2**	1/3 of PV system	1	1817.2
3	1/3 of PV system	3	1817.2	**3**	1/3 of PV system	2	1817.2
4	1/3 of PV system	4	1817.2	**4**	Heating system	4	2456.54
5	1/3 of PV system	5	1817.2	**5**	Glazing and lighting system	5	1620-1790

Table 4.45 : Definition of phases for step-by-step scenarios with six steps (Row-Antalya).

Step No.	Scenario 1 Improvements	Application year	Cost per Flat (TL)	Step No.	Scenario 2 Improvements	Application year	Cost per Flat (TL)
1	Glazing and lighting system	0	1620 - 1790	**1**	1/3 of PV system	0	1799.9
2	Heating system	2	2456.54	**2**	1/3 of PV system	1	1799.9
3	Cooling system	4	3608.74	**3**	1/3 of PV system	2	1799.9
4	1/3 of PV system	5	1799.9	**4**	Heating system	4	2456.54
5	1/3 of PV system	6	1799.9	**5**	Glazing and lighting system	5	1620 - 1790
6	1/3 of PV system	7	1799.9	**6**	Cooling System	7	3608.74

Figure 4.63 and 4.64 are indicating the amount of PEC of each step during defined step-by-step scenarios (Figure 4.63 and Figure 4.64).

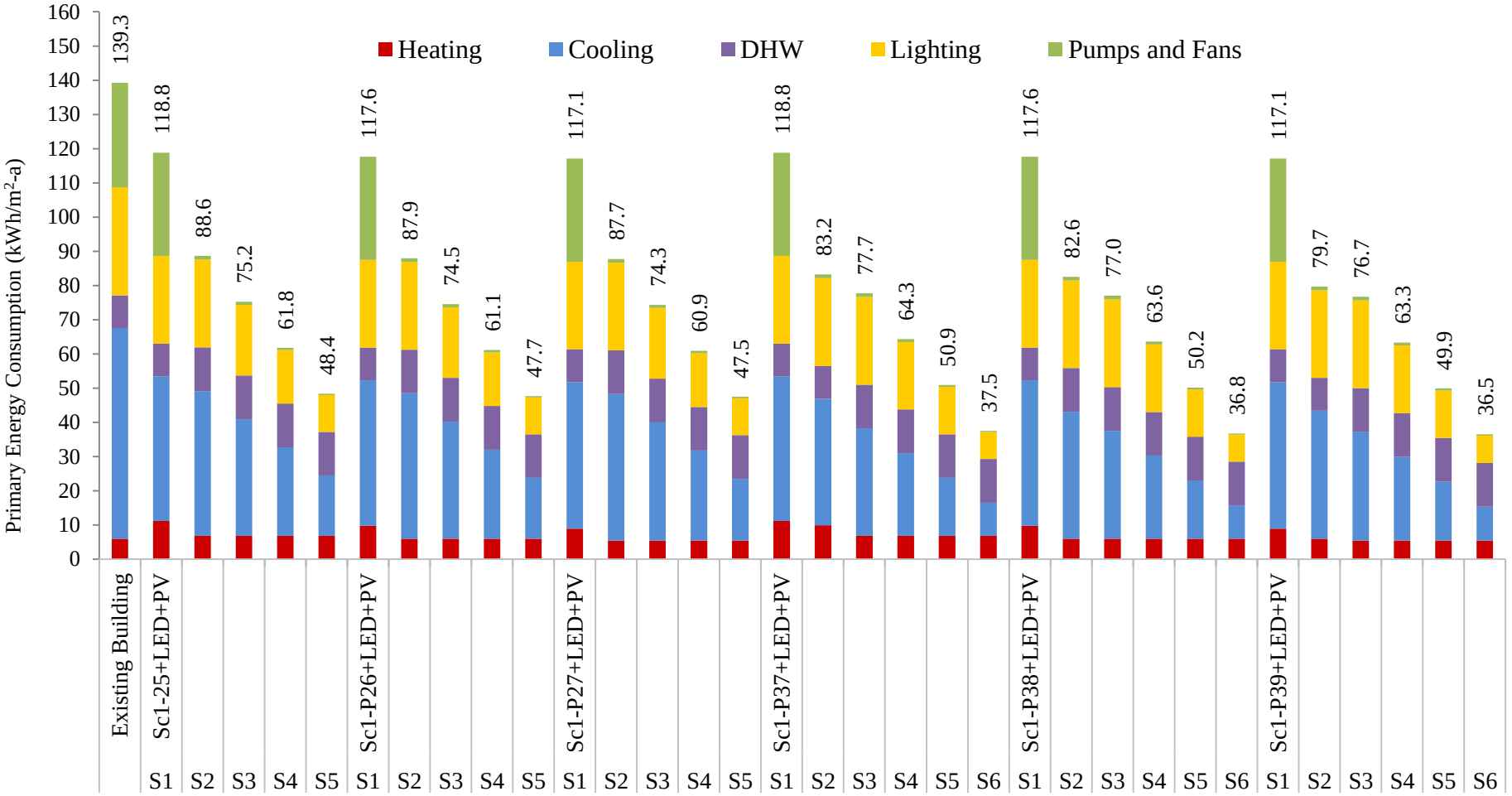

Figure 4.63 : PEC of each step with the first scenario application (Row-Antalya).

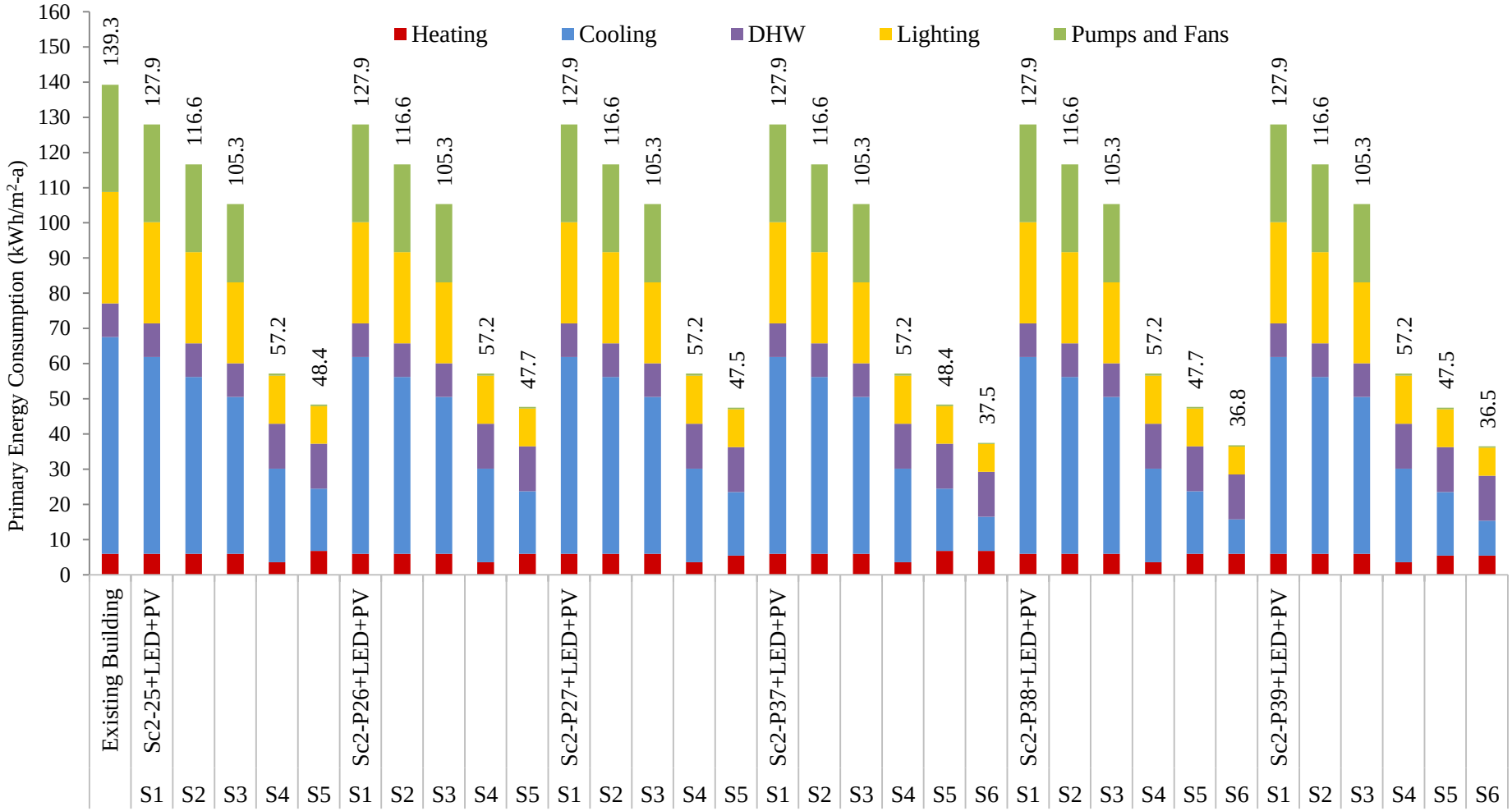

Figure 4.64 : PEC of each step with the second scenario application (Row-Antalya).

The cost of each phase is calculated and defined based on the method indicated in section 3.5. There is a little difference between global cost and PEC of the defined two scenarios. In general, all scenarios have about 52 kWh/m^2 average PEC during calculation period and 385-395 TL/m^2 global cost. The position of these scenarios in the global cost vs. primary energy consumption graph is indicating that in comparison with the cost optimum retrofit scenarios, step-by-step scenarios have just 7% increase in global cost during the calculation period and approximately 24% grow in PEC. This amount is negligible when to compare with the amount of step-by-step scenarios' global cost and PEC saving that are 30% and 63% respectively (Figure 4.65).

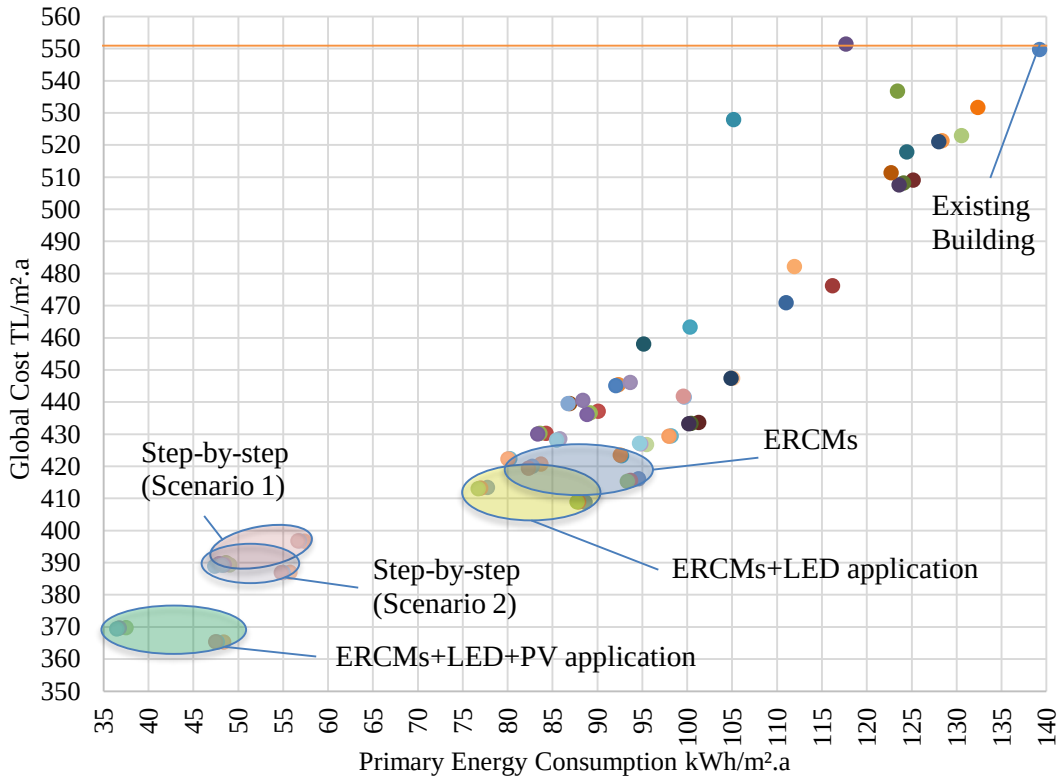

Figure 4.65 : The global cost vs. primary energy consumption graph for one step and step-by-step applications (Row-Antalya).

4.6.2.2 Step-by-step retrofit analyses for the row building located in Erzurum

In this case, all scenarios contain five steps. Heating systems improvements should be applied by the one-year postponement (Table 4.46).

Table 4.46 : Definition of phases for step-by-step scenarios with five steps (Row-Erzurum).

Step No.	Scenario 1 Improvements	Application year	Cost per Flat (TL)	Step No.	Scenario 2 Improvements	Application year	Cost per Flat (TL)
1	Glazing and lighting system	0	1468.12 - 1791.49	**1**	Heating system	1	2456.54
2	Heating system	2	2456.54	**2**	1/3 of PV system	2	1817.2
3	1/3 of PV system	3	1817.2	**3**	1/3 of PV system	3	1817.2
4	1/3 of PV system	4	1817.2	**4**	1/3 of PV system	4	1817.2
5	1/3 of PV system	5	1817.2	**5**	Glazing and lighting system	5	1468.12 - 1791.49

Figure 4.66 is indicating the amount of PEC of each step during defined step-by-step scenarios (Figure 4.66).

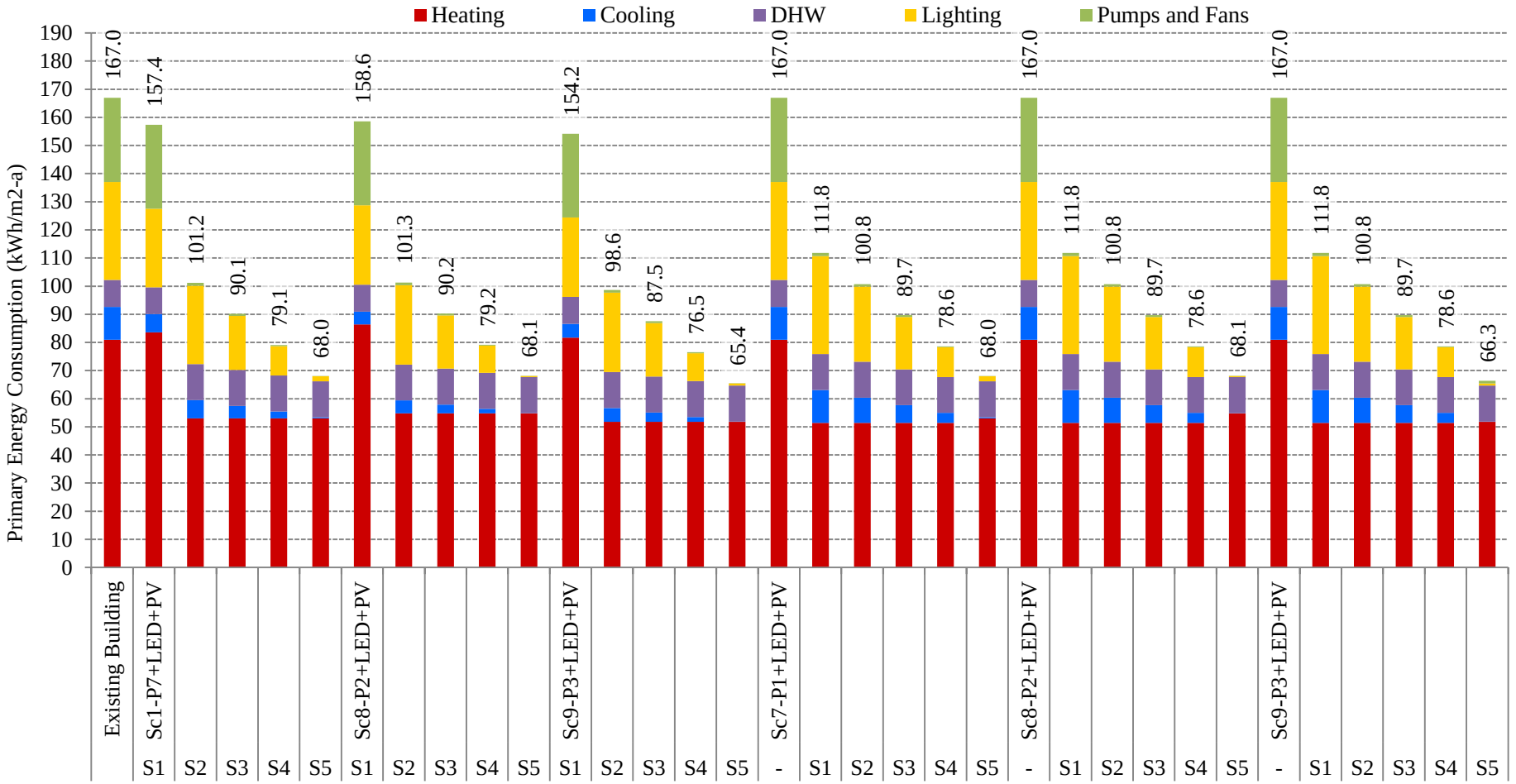

Figure 4.66 : PEC of each step with the first scenario application (Row-Erzurum).

The cost of each phase is calculated and defined based on the method indicated in section 3.5. There is a little difference between global cost and PEC of the defined two scenarios. In general, all scenarios have about 75 kWh/m^2 average PEC during calculation period and 400-410 TL/m^2 global cost. The position of these scenarios in the global cost vs. primary energy consumption graph is indicating that in comparison with optimum retrofit scenarios, step-by-step scenarios have less than 1% increase in global cost during the calculation period, and approximately 9% grow in PEC. This amount is negligible when to compare with the amount of step-by-step scenarios' global cost and PEC saving that are 30% and 55% respectively (Figure 4.67).

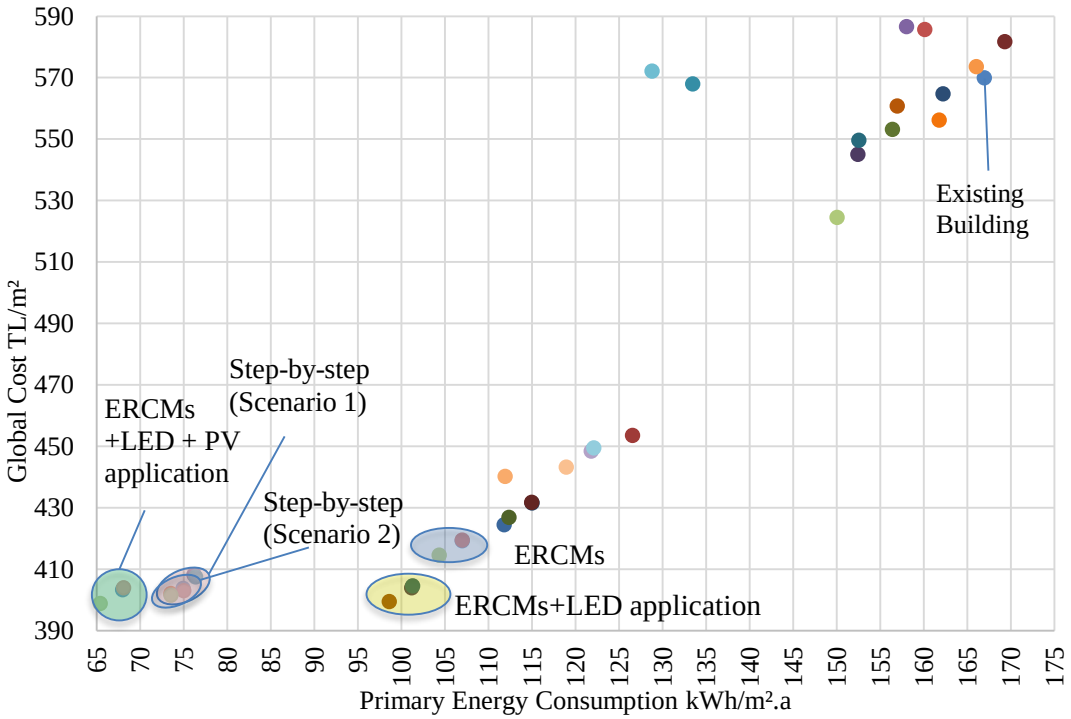

Figure 4.67 : The global cost vs. primary energy consumption graph for one step and step-by-step applications (Row-Erzurum).

4.6.2.3 Step-by-step retrofit analyses for the row building located in Istanbul

In this building, all scenarios should include five steps. It is not necessary to make any postponement among measures' applications (Table 4.47).

Table 4.47 : Definition of phases for step-by-step scenarios (Row-Erzurum).

Step No.	Scenario 1 Improvements	Application year	Cost per Flat (TL)	Step No.	Scenario 2 Improvements	Application year	Cost per Flat (TL)
1	Glazing and lighting system	0	1618.7 – 1791.5	**1**	Heating system	0	2133.7
2	Heating system	1	2133.7	**2**	1/3 of PV system	1	1817.2
3	1/3 of PV system	2	1817.2	**3**	1/3 of PV system	2	1817.2
4	1/3 of PV system	3	1817.2	**4**	1/3 of PV system	3	1817.2
5	1/3 of PV system	4	1817.2	**5**	Glazing and lighting system	4	1618.7 – 1791.5

Figure 4.68 is indicating the amount of PEC of each step during defined step-by-step scenarios (Figure 4.68).

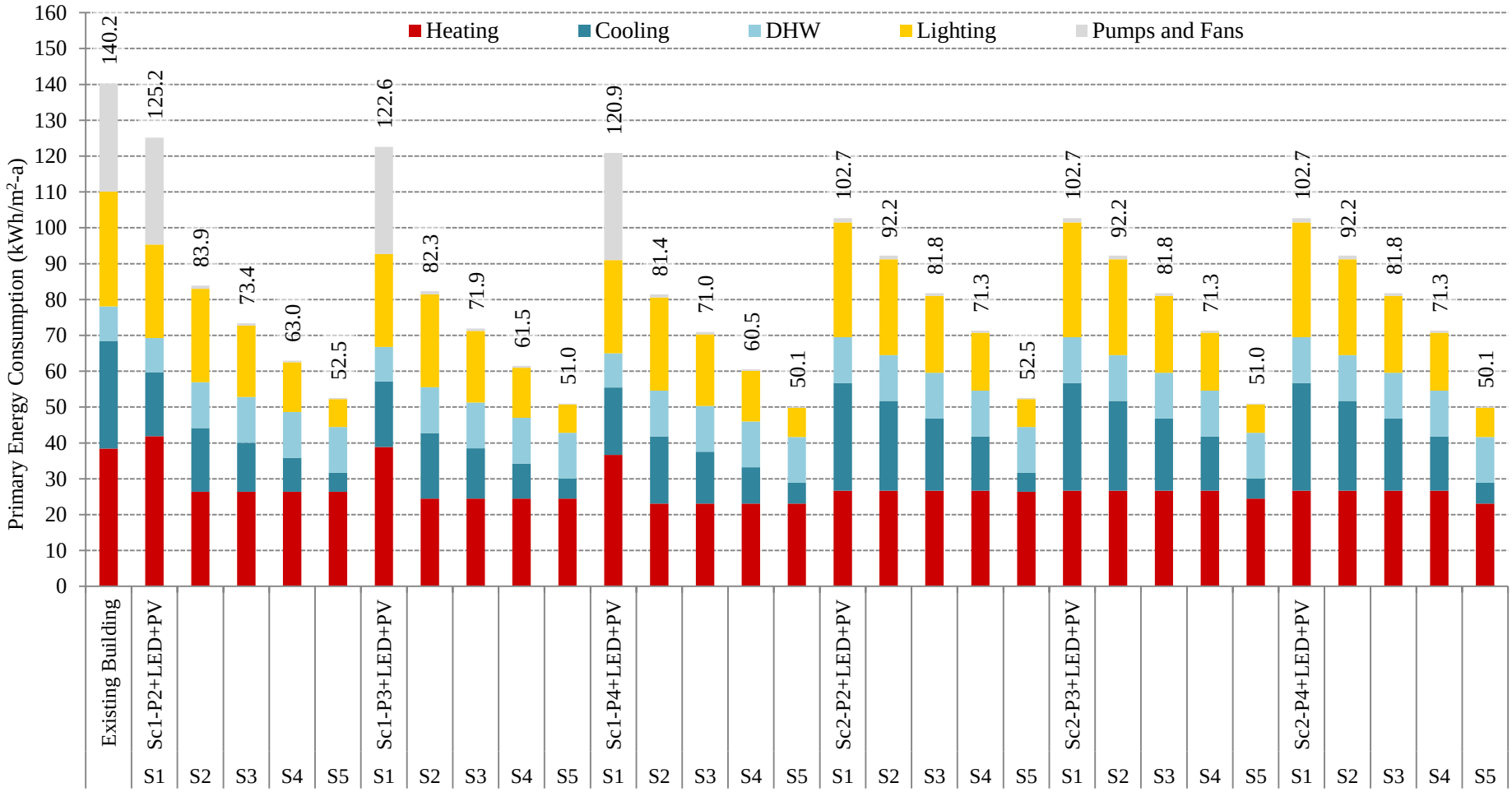

Figure 4.68 : PEC of each step with the first scenario application (Row-Erzurum).

The cost of each phase is calculated and defined based on the method indicated in section 3.5. Similar to previous cases, there is a little difference between global cost and PEC of the defined two scenarios. In general, all step-by-step retrofit scenarios have about 55 kWh/m^2 average PEC during calculation period and 360-365 TL/m^2 global cost. The position of these scenarios in the global cost vs. primary energy consumption graph is indicating that in comparison with optimum retrofit scenarios, step-by-step scenarios have just 6% increase in global cost during the calculation period and approximately 10% grow in PEC. This amount is negligible when to compare with the amount of step-by-step scenarios' global cost and PEC saving that are 30% and 60% respectively (Figure 5.69).

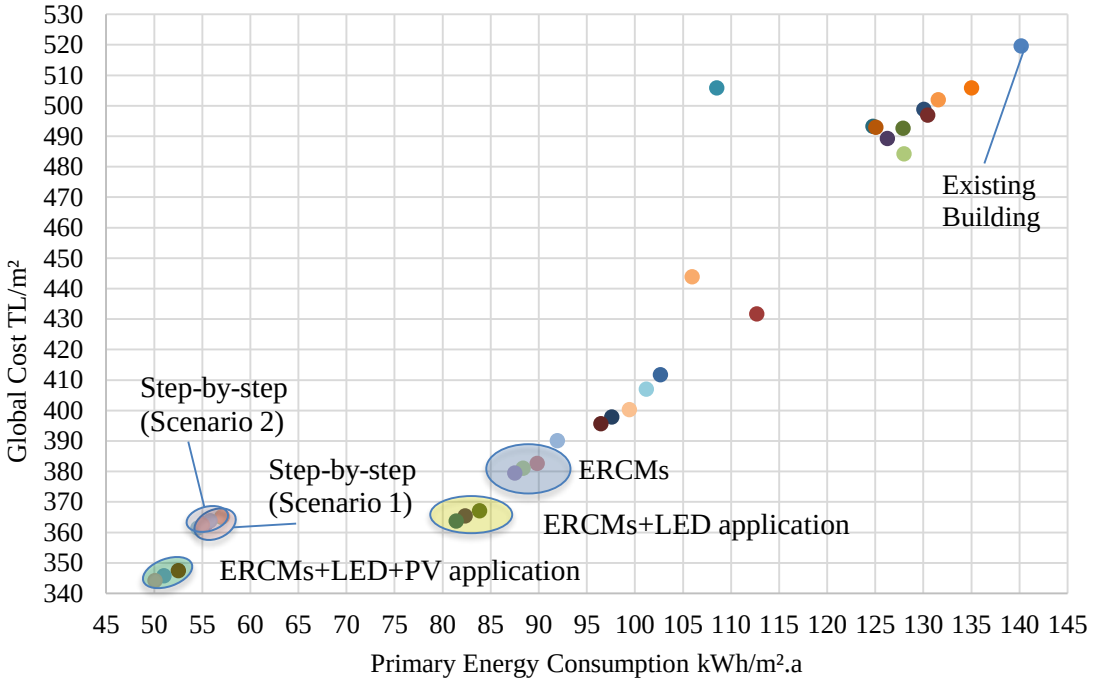

Figure 4.69 : The global cost vs. primary energy consumption graph for one step and step-by-step applications (Row-Erzurum).

4.7 Undertaking a sensitivity analysis

As stated in section 3.6, undertaking a sensitivity analysis is obligated through EPBD-Recast to determine the effect of different economic variation on the results of the cost analyses.

4.7.1 Detached buildings

The results of sensitivity analyses with two different discount rate as for the buildings located in the representative cities are indicated in the followings:

4.7.1.1 Results of sensitivity analyses for the detached building located in Antalya

The result of sensitivity analysis with 3% discount rate is showing that there aren't any substantial changes in the order of related measures while the amount of existing building's global cost increases from 562TL/m^2 to about 644 TL/m^2. At the same time, the global costs of optimum scenarios are increased from 390-400 TL/m^2 to 430-440 TL/m^2. Step-by-step scenarios are also containing about 40 TL/m^2 growth in their global cost (Figure 4.70).

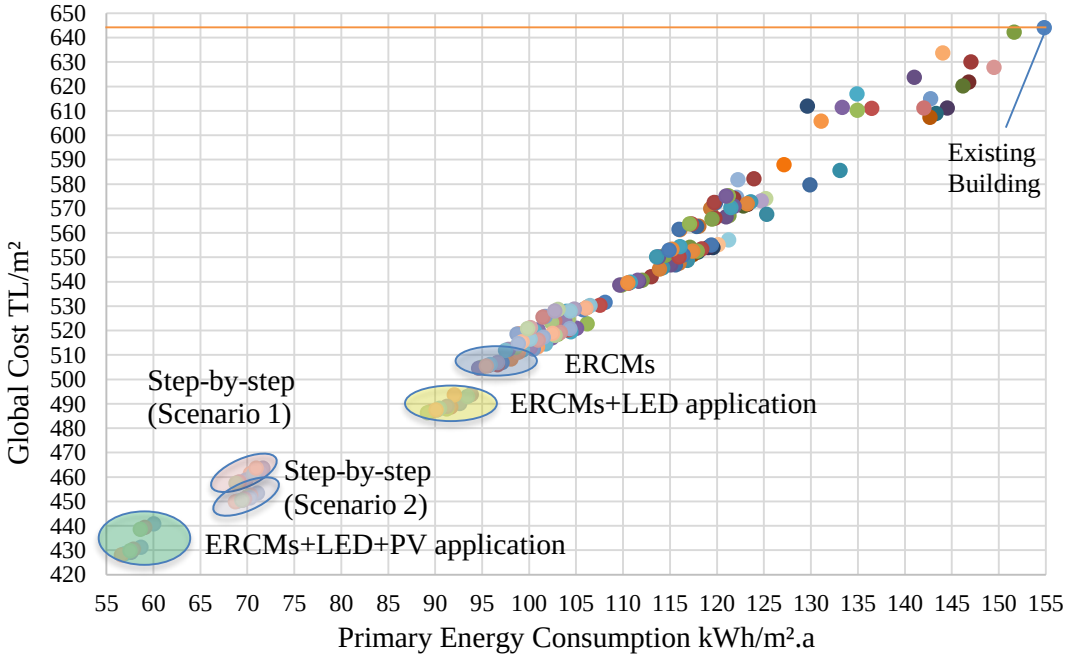

Figure 4.70 : The global cost vs. primary energy consumption graph with 3% discount rate (Detached-Antalya).

Another sensitivity analysis has been carried out by increasing the discount rate from 9.95% to 14%. New conditions provide a significant gap even between new and previous single measures. Thus, it can be concluded that to reach the intended results; it is necessary to choose correct economic variations during calculations (Figure 4.71).

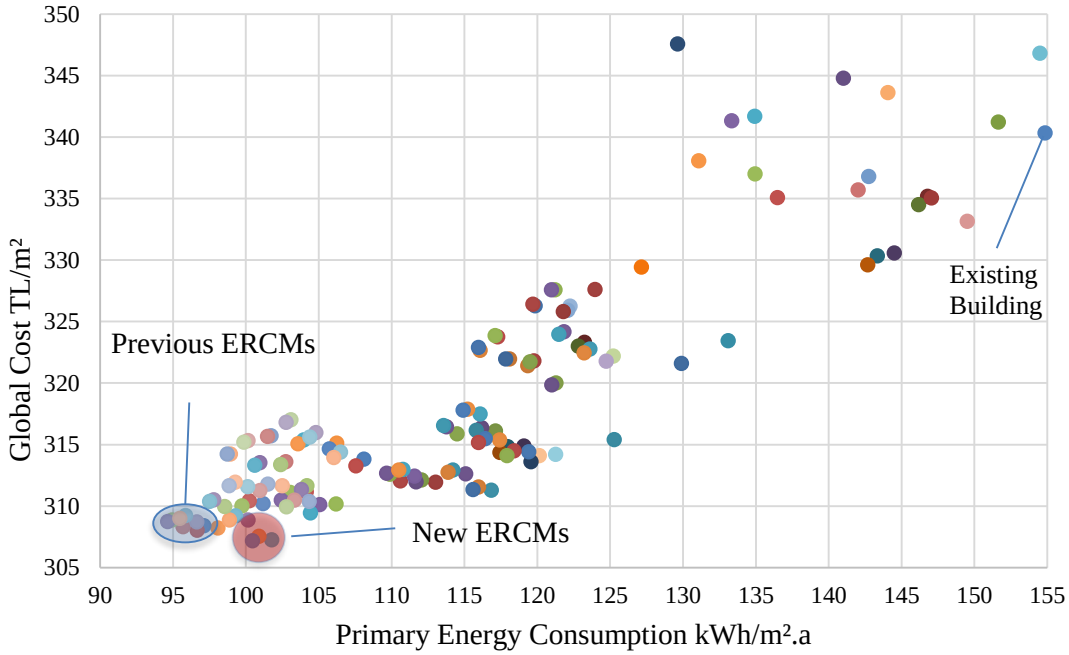

Figure 4.71 : The global cost vs. primary energy consumption graph for single measures with 14% discount rate (Detached-Antalya).

4.7.1.2 Results of sensitivity analyses for the detached building located in Erzurum

The result of sensitivity analysis with 3% discount rate is showing that there aren't any substantial changes in the order of related measures while the amount of existing building's global cost increases from 603TL/m^2 to about 685 TL/m^2. At the same time, the global costs of optimum scenarios are increased from 400-420 TL/m^2 to 440-460 TL/m^2. Step-by-step scenarios are also containing about 50 TL/m^2 growth in their global cost (Figure 4.72).

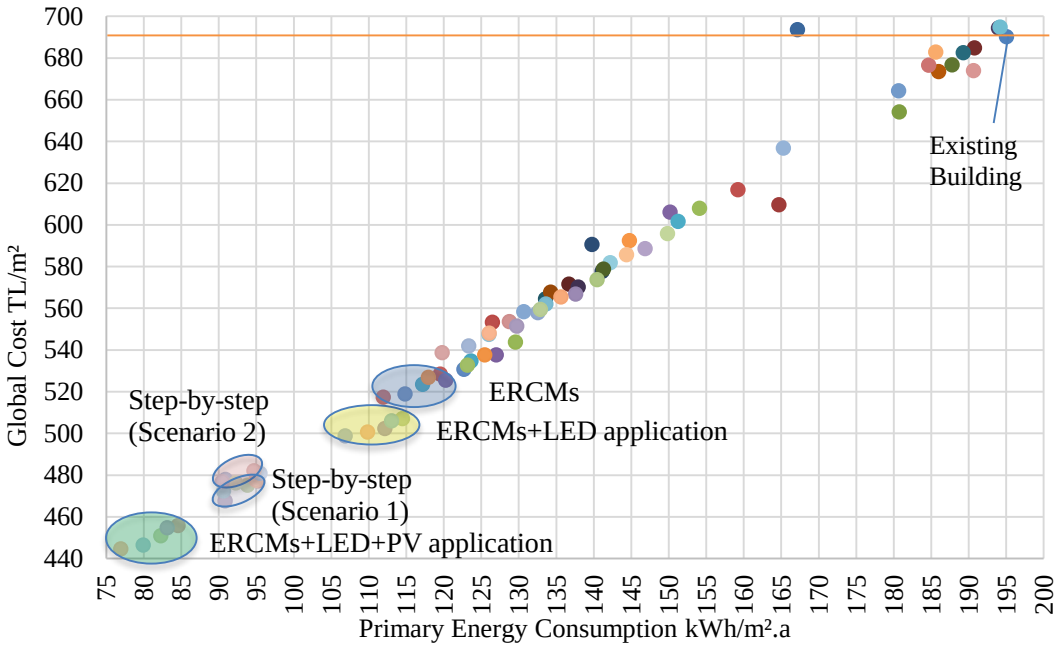

Figure 4.72 : The global cost vs. primary energy consumption graph with 3% discount rate (Detached-Erzurum).

The result of analysis with 14% discount rate is providing a significant gap between new and previous optimum architectural and mechanical combined measures. Also, it can be seen that the amount of global cost improvement is very decreased in this new situation. Thus, it can be concluded that to reach the intended results; it is necessary to choose correct economic variations during calculations (Figure 4.73).

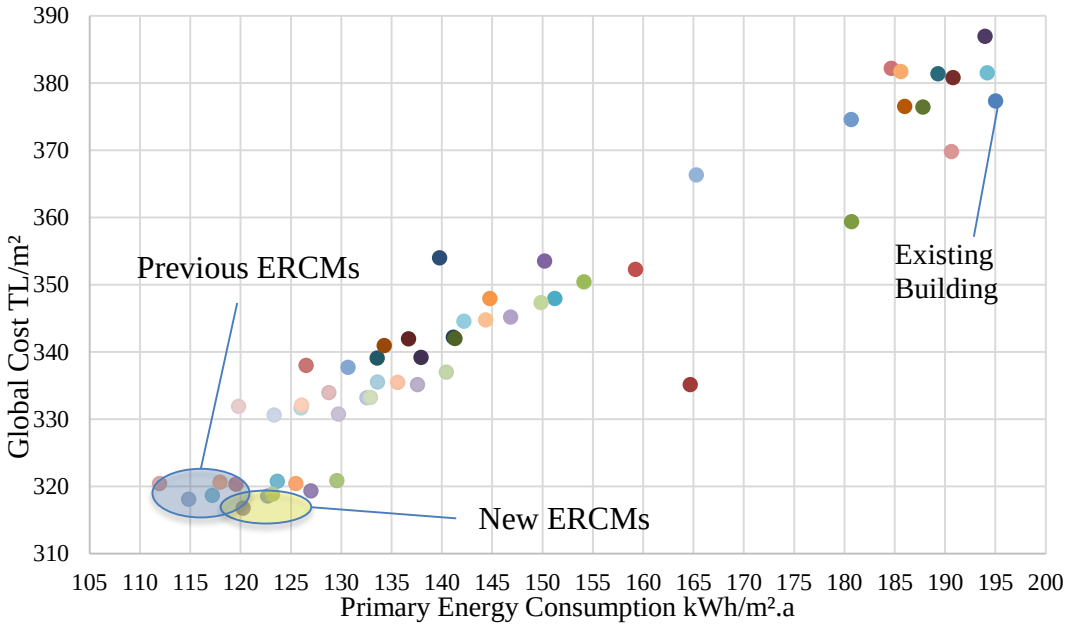

Figure 4.73 : The global cost vs. primary energy consumption graph with 14% discount rate (Detached-Erzurum).

4.7.1.3 Results of sensitivity analyses for the detached building located in Istanbul

The result of sensitivity analysis with 3% discount rate is showing that there aren't any substantial changes in the order of related measures while the amount of existing building's global cost increases from approximately 490 TL/m^2 to about 560 TL/m^2. At the same time, the global costs of optimum scenarios are increased from about 380 TL/m^2 to approximately 420 TL/m^2. Step-by-step scenarios are also containing about 40 TL/m^2 growth in their global cost (Figure 4.74).

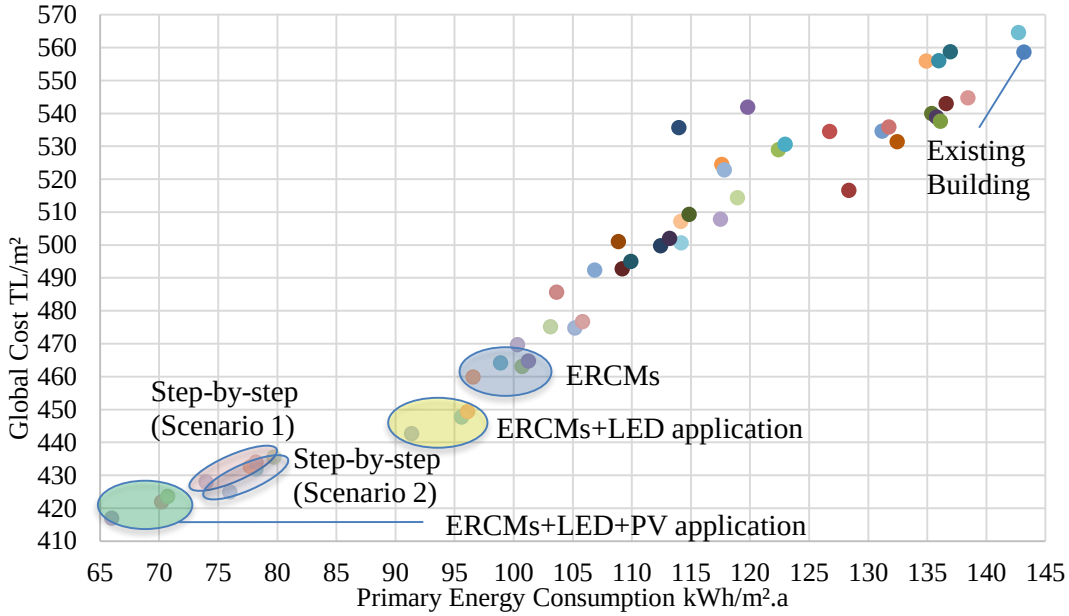

Figure 4.74 : The global cost vs. primary energy consumption graph with 3% discount rate (Detached-Istanbul).

The result of analysis with 14% discount rate is providing a significant gap between new and previous single measures. Also, it can be seen that the amounts of global costs improvements are very decreased in this new situation. Compared to the previous condition, there are lots of measures that are not cost effective. Thus, it can be concluded that to reach the intended results; it is necessary to choose current economic variations during calculations (Figure 4.75).

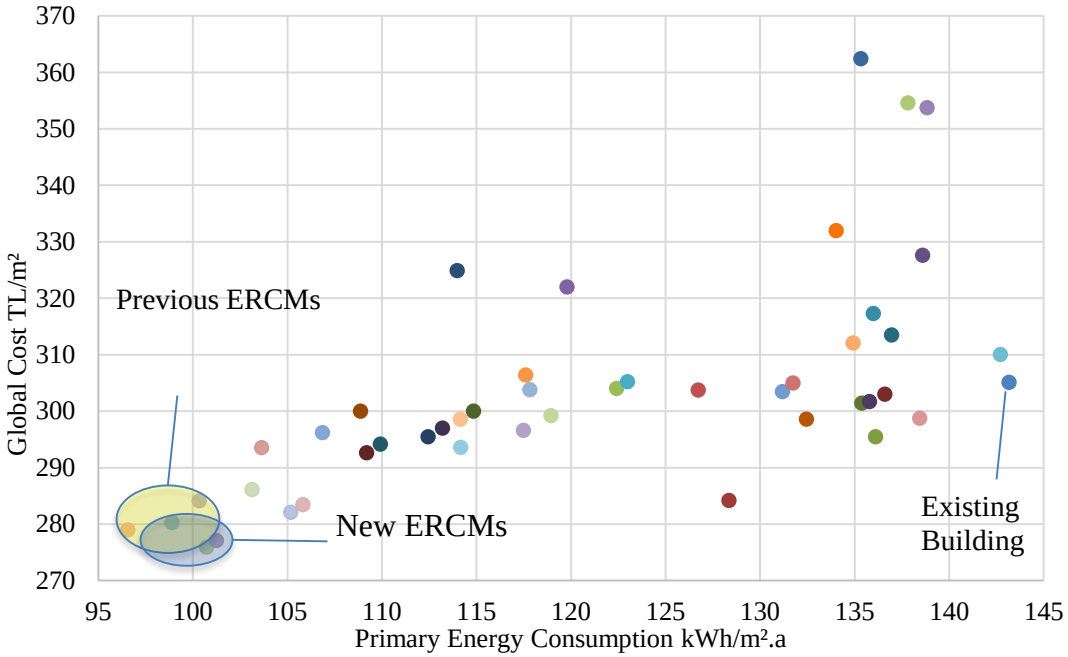

Figure 4.75 : The global cost vs. primary energy consumption graph with 14% discount rate (Detached-Istanbul).

4.7.2 Row buildings

The results of sensitivity analyses with two different discount rate as for the row buildings located in the representative cities are indicated in the followings:

4.7.2.1 Results of sensitivity analyses for the row building located in Antalya

The result of sensitivity analysis with 3% discount rate is showing that there aren't any substantial changes in the order of related measures while the amount of existing building's global cost increases from about 550TL/m^2 to about 630 TL/m^2. At the same time, the global costs of optimum scenarios are increased from 365-370 TL/m^2 to about 400 TL/m^2. Step-by-step scenarios are also containing about 30 TL/m^2 growth in their global cost (Figure 4.76).

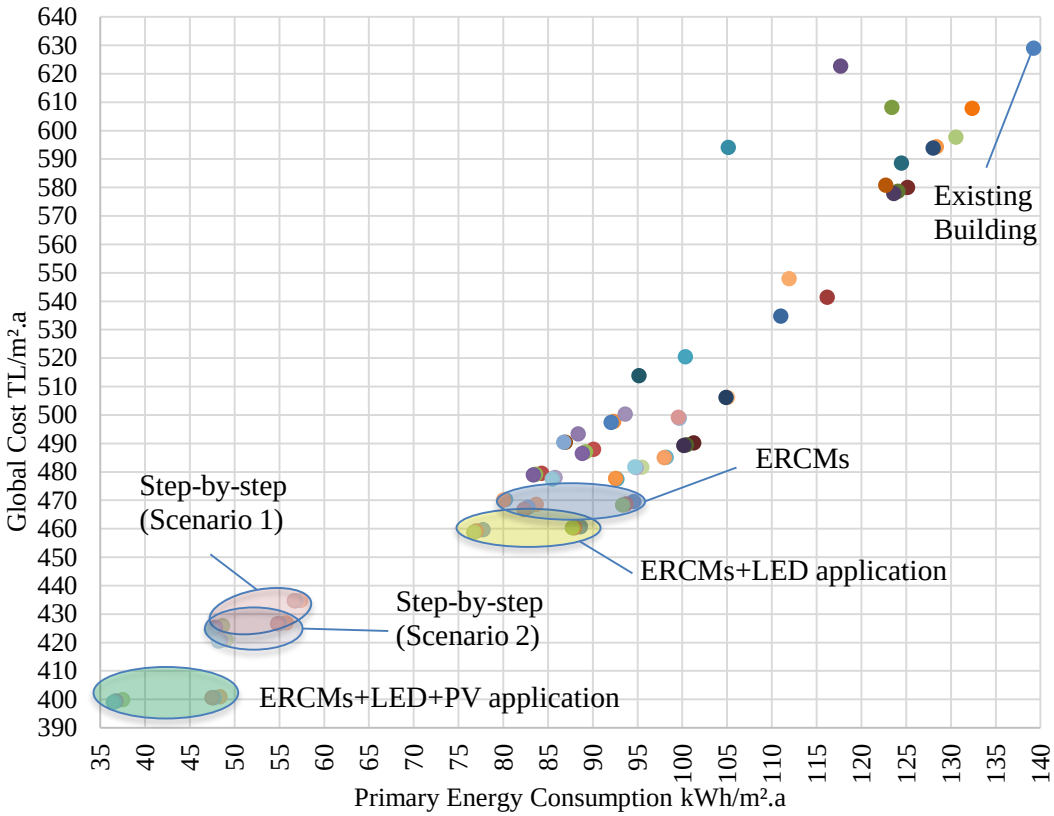

Figure 4.76 : The global cost vs. primary energy consumption graph with 3% discount rate (Row-Antalya).

Another sensitivity analysis has been carried out by increasing the discount rate from 9.95% to 14%. New conditions provide a gap even between new and previous single measures. In this condition, some actions that were reducing the global cast previously, are increasing it. Single measures like cooling system improvements are not cost effective. Thus, a combination of them is not located in the optimum level. In the new situation, P37, P38, and P39 are not included in optimum architectural and mechanical combination measures as they include cooling system improvement. LED and PV application also are not affecting so much on global cost. They can decrease global cost by just 8 TL/m^2 that is very low. Step-by-step scenarios are also not rational to use as they lead to higher global cost. Optimum packages are decreasing just 21% of the global cost; it is very lower than 32% fall when the discount rate is 9.95% (Figure 4.77).

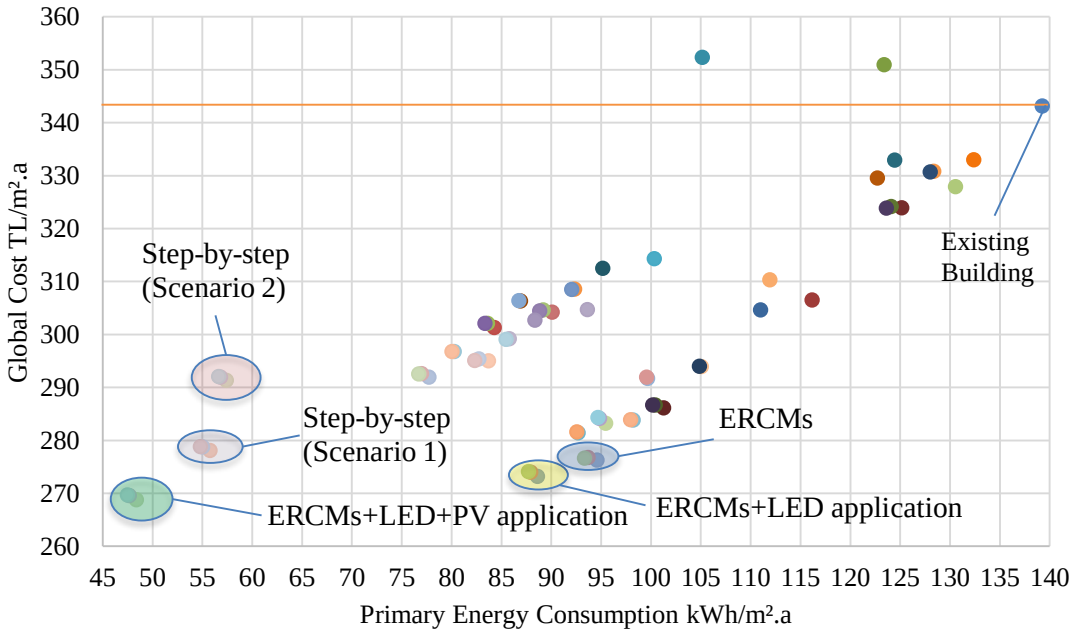

Figure 4.77 : The global cost vs. primary energy consumption graph for single measures with 14% discount rate (Row-Antalya).

4.7.2.2 Results of sensitivity analyses for the row building located in Erzurum

The result of sensitivity analysis with 3% discount rate is showing that there aren't any substantial changes in the order of related measures while the amount of existing building's global cost increases from 570 TL/m^2 to about 654 TL/m^2. At the same time, the global costs of optimum scenarios are increased from 400-410 TL/m^2 to 440-450 TL/m^2. Step-by-step scenarios are also containing about 40 TL/m^2 growth in their global cost. The most significant incidence, in this case, is about 10 TL/m2 decrease in global cost when to compare the global cost of LED application and PV + LED application on ERCMs (Figure 4.78).

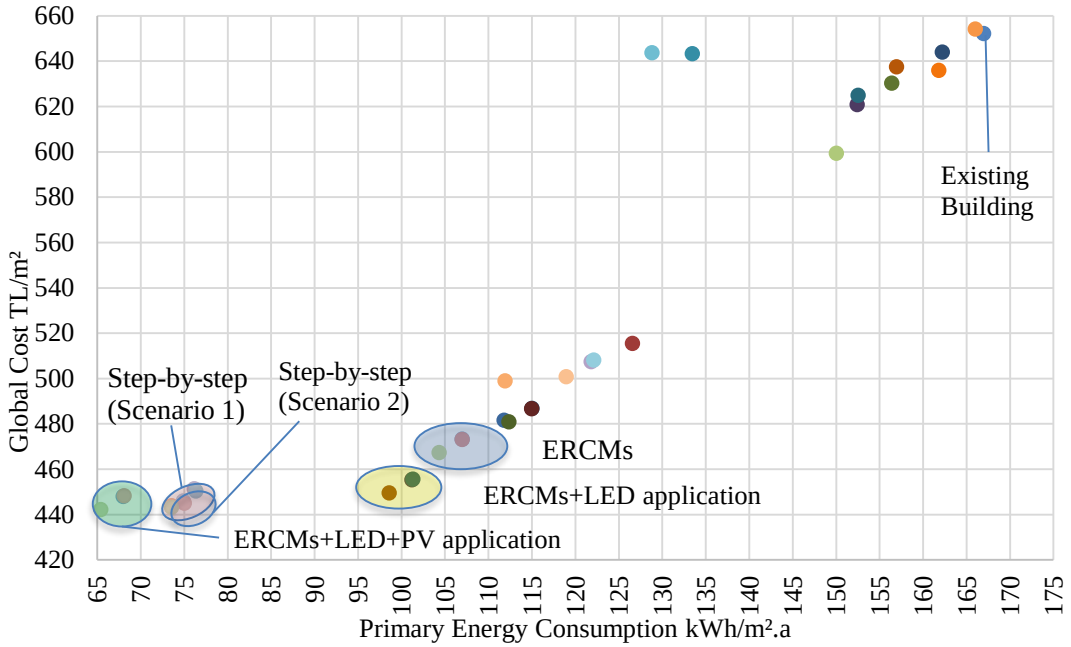

Figure 4.78 : The global cost vs. primary energy consumption graph using 3% discount rate (Row-Erzurum).

The result of analysis with 14% discount rate is providing a significant gap between new and previous PV system application contained packages. In the past circumstances, these packages were decreasing the global cost while at the new condition they are growing it. Thus, in this case, the PV application is not rational to use. Thus, it can be concluded that to reach the intended results; it is necessary to choose correct economic variations during calculations (Figure 4.79).

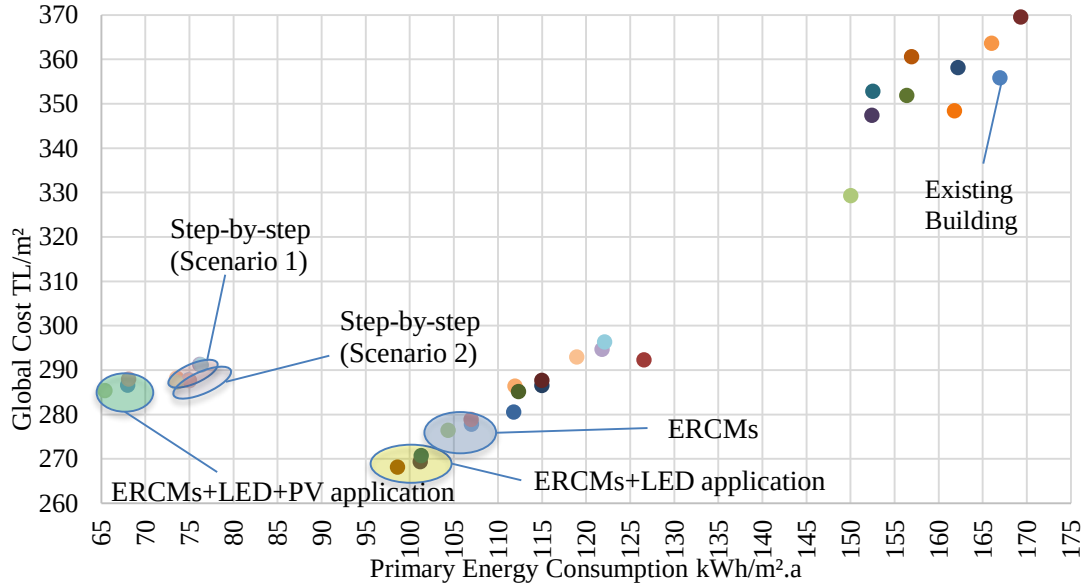

Figure 4.79 : The global cost vs. primary energy consumption graph using 14% discount rate (Row-Erzurum).

4.7.2.3 Results of sensitivity analyses for the row building located in Istanbul

The result of sensitivity analysis with 3% discount rate is showing that there aren't any substantial changes in the order of related measures while the amount of existing building's global cost increases from approximately 520 TL/m^2 to about 595 TL/m^2. At the same time, the global costs of optimum scenarios are increased from about 345 TL/m^2 to approximately 380 TL/m^2. Step-by-step scenarios are also containing about 40 TL/m^2 growth in their global cost (Figure 4.80).

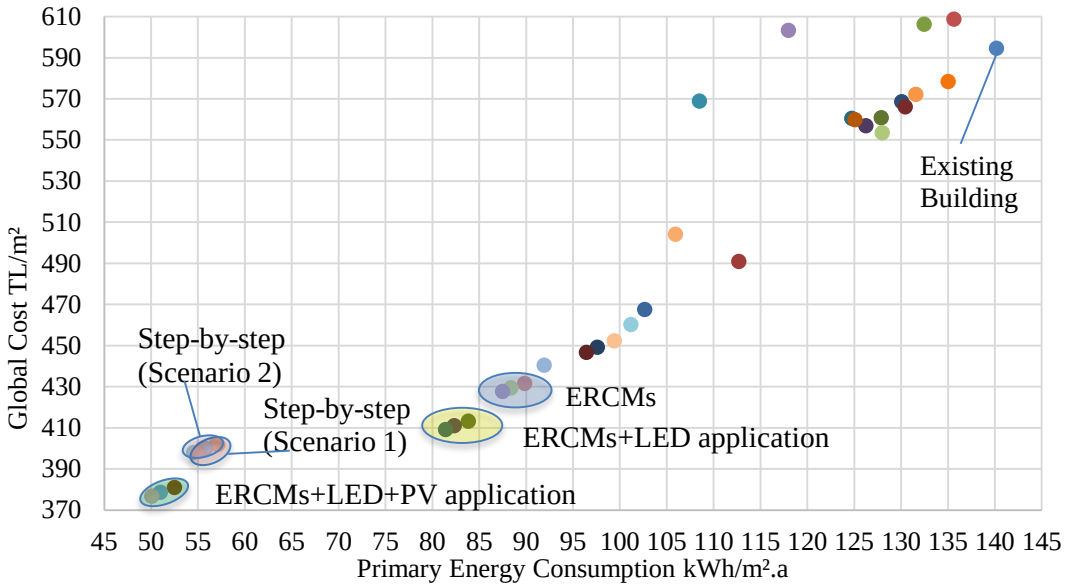

Figure 4.80 : The global cost vs. primary energy consumption graph with 3% discount rate (Row-Istanbul).

The result of analysis with 14% discount rate is providing a gap between new and previous single measures. At the new situation, PV application is not reducing the global cost. Thus, it is irrational to use in the calculation. Also, it can be seen that the amounts of global costs improvements are very decreased. Thus, it can be concluded that to reach the intended results; it is necessary to choose correct economic variations during calculations (Figure 4.81).

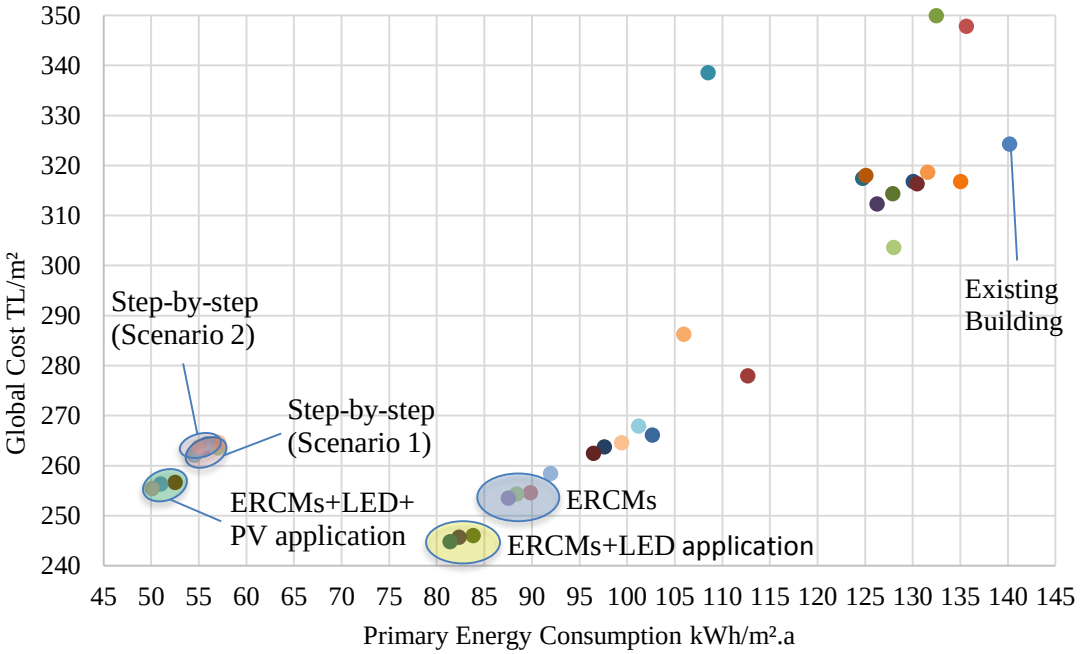

Figure 4.81 : The global cost vs. primary energy consumption graph with 14% discount rate (Row-Istanbul).

5. DISCUSSION

The study established the methodology of step-by-step retrofit to achieve the deep retrofit of the residential buildings. By using this methodology, it is possible to achieve deep retrofit level through affordable actions.

Have a glimpse to the most optimum scenario for the existing building in each climate make it clear that from 6 measures that were created for opaque system improvements in the detached building, just the measure that has a U-value 25% better than TS825-2013 level is leading the retrofit action to the optimum level. In the row building, the opaque system amendments are not necessary. Except the row building located in Antalya, the glazing system of the buildings should have a U-value equal to 1.1 W/m²K, a T_{vis} equal to 0.71 and a SHGC equal to 0.44. The glazing system of the row building located in Antalya should have a U-value equal to 1.6 W/m²K. Shading device application and heating component replacement are not necessary to reach the optimum point in any building. Central condensing boiler application is necessary for all buildings. Cooling system improvement is required in the buildings located in Antalya's climate. PV application and the replacement of the lighting system with LED lamps is necessary for all of the buildings (Table 5.1).

Table 5.1: Characteristics of the most optimum scenario for each of buildings.

	Detached			**Row**		
	Antalya	**Erzurum**	**Istanbul**	**Antalya**	**Erzurum**	**Istanbul**
Opaque System	U_{opaque} 25% (S5)	U_{opaque} 25% (S5)	U_{opaque} 25% (S5)	Existing	Existing	Existing
Glazing System	5th Glazing (S11)	5th Glazing (S11)	5th Glazing (S11)	3th Glazing (S7)	5th Glazing (S9)	5th Glazing (S9)
Shading Device	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Heating System	Cond. Boiler (S19)	Cond. Boiler (S19)	Cond. Boiler (S19)	Cond. Boiler (S18)	Cond. Boiler (S18)	Cond. Boiler (S18)
Heating Component	Existing	Existing	Existing	Existing	Existing	Existing

Table 5.1 (continued): Characteristics of the most optimum scenario for each of buildings.

	Detached			Row		
	Antalya	**Erzurum**	**Istanbul**	**Antalya**	**Erzurum**	**Istanbul**
Cooling System	COP 3.5 (S22)	Existing	Existing	COP 3.5 (S20)	Existing	Existing
Renewable System	P.V. (S24)	P.V. (S24)	P.V. (S24)	P.V. (S24)	P.V. (S24)	P.V. (S24)
Lighting System	LED (S25)	LED (S25)	LED (S25)	LED (S25)	LED (S25)	LED (S25)

Table 5.2 provides an overview of the most significant results of the cost-optimality study in relation in three cities that were deemed representative of the different climates in Turkey: Antalya, Istanbul, and Erzurum. As the table indicates, Antalya offers the biggest opportunity for achieving primary energy savings, while in the detached buildings, Istanbul and in the row buildings Erzurum has the lowest opportunity. It means that retrofit would not be as energy efficient in Istanbul and Erzurum as it would be in Antalya. It is valid also for CO_2 emission. From Global Cost (G.C.) point of view, the situation is complicated. In the detached buildings, Erzurum offers the biggest opportunity, while Istanbul has the lowest opportunity. In the row buildings, retrofits in Istanbul is the most and in Erzurum is the least efficient. Flat owners of the detached buildings in Antalya and Erzurum would be required to pay about 1.5 times as much as those living in the row buildings located in Istanbul and Erzurum to reach the optimum point. Optimum scenarios have 8 to 10-year payback period. At least yearly PEC saving is 77.19 kWh/m^2. While at least G.C. and CO_2 emission savings are 111.8 TL/m^2 and 19.69 Kg/m^2.a respectively. The divisions should apply to implement the measures as the initial investment costs for homeowners in these regions are not acceptable (Table 5.2).

Table 5.2: Summary of results for the most optimum scenarios.

	Detached			Row		
	Antalya	**Erzurum**	**Istanbul**	**Antalya**	**Erzurum**	**Istanbul**
Existing Building's PEC (kWh/m^2)	154.86	195.03	143.17	139.25	166.97	140.20
Existing Building's CO_2 Emission ($Kg/m^2.a$)	41.78	48.54	36.99	38.02	42.43	36.86
Existing Building's G.C. (TL/m^2)	562.68	603.10	488.07	549.65	569.85	519.57
Optimum Scenario's PEC ($kWh/m^2.a$)	56.61	76.95	65.98	36.47	65.42	50.10
PEC Saving ($kWh/m^2.a$)	98.25	118.08	77.19	102.78	101.55	90.1
PEC Saving (%)	63.44	60.54	53.91	73.81	60.82	64.27
Optimum Scenario's G.C. (TL/m^2)	388.74	405.56	376.27	369.34	398.78	344.11
G.C. Saving (TL/m^2)	173.94	197.54	111.8	180.31	171.07	175.46
G.C. Saving (%)	30.91	32.75	22.91	32.80	30.02	33.77
Optimum Scenario's CO_2 Emission ($Kg/m^2.a$)	15.50	19.31	17.30	9.34	15.34	12.35
CO_2 Emission Saving ($Kg/m^2.a$)	26.28	29.23	19.69	28.68	27.09	24.51
CO_2 Emission Saving (%)	62.90	60.22	53.23	75.43	63.85	66.49
Optimum Scenario's I.I.C. (TL)	217958	218065.5	177953	133084	96996	94768
Optimum Scenario's I.I.C. per Flat (TL)	14530.56	14537.7	11863.5	13308.4	9699.6	9476.8
Optimum Scenario's P.P. (year)	8.5	8	9.5	10	8	8.5

Table 5.3 provides an overview of the most significant results of the step-by-step retrofit analyzes in related cities. The retrofit plans should be implemented in five to seven phases. In half of possible step-by-step scenarios, the first scenario that starts from the measure with minimum payment and lasts with maximum payment for an owner is the best one and in another half, the second scenario that starts with the maximum energy saving measure and last with minimum energy conservation measure is the best. The amount of PEC and CO_2 emission savings are reduced by using step-by-step scenarios, but it is not more than 8.3% in any cases. The amount of global cost saving will be reduced not more than 3.89%. Except the row building located in Antalya, all step-by-step scenarios have less than 12-years payback period starting from the decision-making year. At least yearly PEC saving is 67.19 kWh/m^2.

While at least G.C. and CO_2 emission savings are 103.8 TL/m^2 and 16.62 Kg/m^2.a respectively (Table 5.3).

Table 5.3: Summary of the results for the most practical step-by-step scenarios.

	Detached			**Row**		
	Antalya	**Erzurum**	**Istanbul**	**Antalya**	**Erzurum**	**Istanbul**
Optimum Step-by-step Scenario	Sc2	Sc1	Sc2	Sc1	Sc2	Sc1
Number of Stages for Optimum Step-by-step Application	7	7	6	6	5	5
Step-by-step Scenario's PEC (kWh/m^2.a)	68.73	90.88	75.98	47.4	73.53	54.54
PEC saving (kWh/m^2.a)	86.13	104.15	67.19	91.85	93.44	85.66
PEC saving (%)	55.62	53.40	46.93	65.96	55.96	61.10
PEC saving reduction (%)	-7.82	-7.14	-6.98	-7.85	-4.86	-3.17
Step-by-step Scenario's G.C. (TL/m^2)	410.66	425.82	384.27	388.85	401.47	361.4
G.C. saving (TL/m^2)	152.02	177.28	103.8	160.8	168.38	158.17
G.C. saving (%)	27.02	29.39	21.27	29.25	29.55	30.44
G.C. saving reduction (%)	-3.89	-3.36	-1.64	-3.55	-0.47	-3.33
Step-by-step Scenario's CO_2 Emission (Kg/m^2.a)	18.72	22.75	20.37	12.38	17.56	13.57
CO_2 Emission saving (Kg/m^2.a)	23.06	25.79	16.62	25.64	24.87	23.29
CO_2 Emission saving (%)	55.19	53.13	44.93	67.44	58.61	63.19
CO_2 Emission saving reduction (%)	-7.71	-7.09	-8.30	-7.99	-5.24	-3.30
Step-by-step Scenario's P.P. (year)	10.5	10	11	14	11	11.5

By comparing the results of the global cost vs. PEC graph in three different climates in Turkey, it is possible to define that the buildings located in Erzurum that is representing the cold climate of Turkey are the most inefficient buildings from cost and energy consumption points of view. Hence, EER of residential buildings built in a cold climate in Turkey have priority and provide more benefits in comparison to a building constructed in other climates. From a global cost point of view, the buildings that are located in Antalya are inefficient compared to the buildings located in Istanbul. While in comparison with the detached building located in Istanbul, the Antalya's case

is more efficient from primary energy consumption point of view. In contrast, between row buildings located in Istanbul and Antalya, the Istanbul's case is a little bit more efficient than Antalya's case. After renovation even with step-by-step scenarios, the distance between locations of the buildings in global cost vs. PEC graph will be close to each other in compare with before renovation locations. Post-renovation location of the buildings on cost-optimality graph reveals that the buildings located in Erzurum will be consuming more primary energy and lead to higher global cost compared to the other buildings (Figure 5.1 and Figure 5.2).

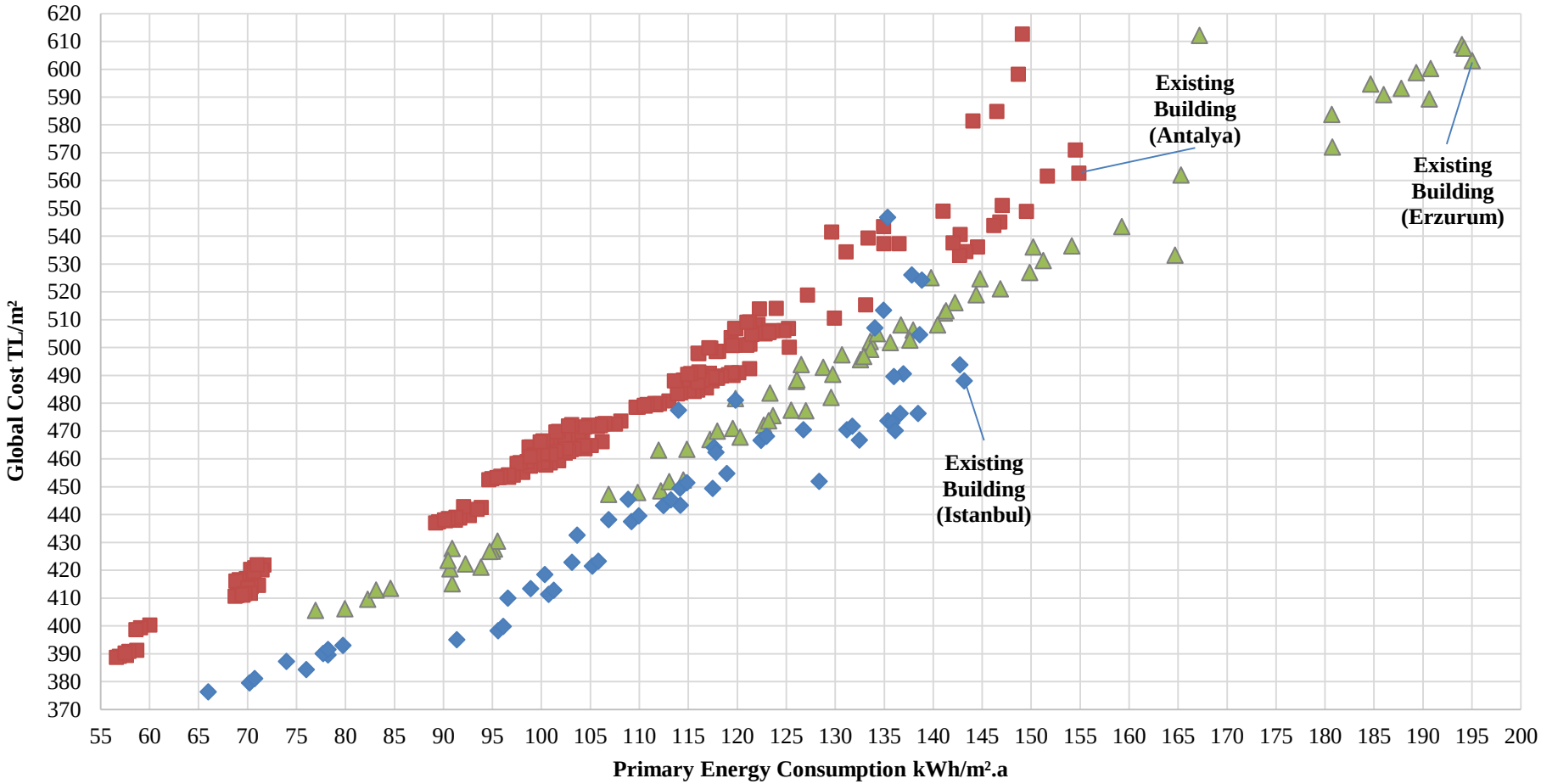

Figure 5.1 : The global cost vs. primary energy consumption graph for detached buildings.

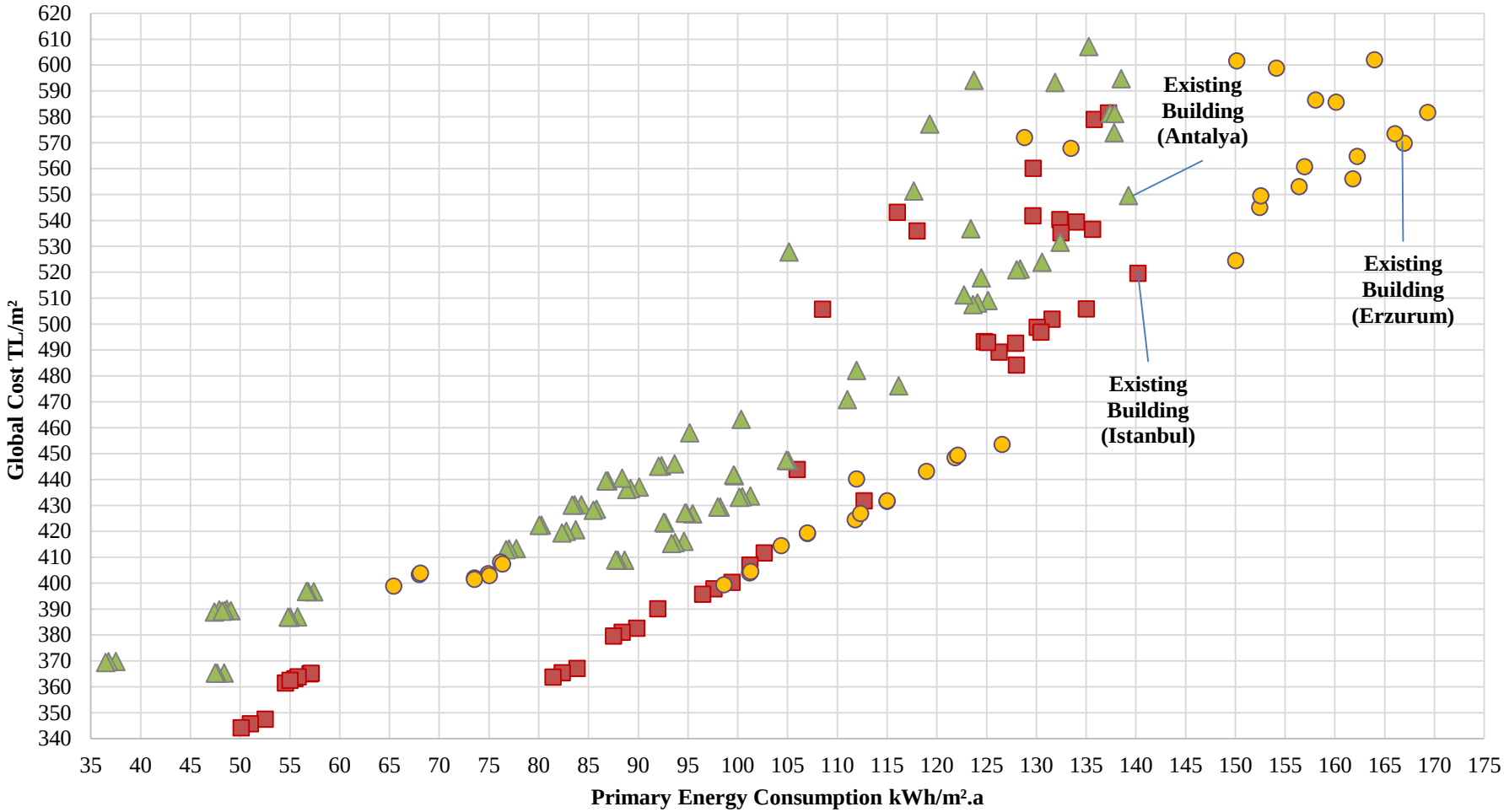

Figure 5.2 : The global cost vs. primary energy consumption graph for row buildings.

5.1 Country-Based Impacts of the Study

According to TÜİK statistics, there are 2,124,186 residential apartment buildings constructed between 1980 and 2008. The occupied area of these buildings is 841,936,541.4 m^2. Based on results of step-by-step analyze in this study, in apartment buildings, there are at least 67.19 $kWh/m^2.a$ PEC and 16.62 $Kg/m^2.a$ CO_2 emission saving potential per year. Moreover, the G.C. potential for 30 years is at least 103.8 TL/m^2. If the yearly retrofit rate is fixed at 3%, that is the desired amount, recommended by EU Commission, 1,697 GWh primary energy will be saved up to the time that all buildings are retrofitted. During this period, 419,789 Tons of CO_2 emissions will be reduced each year.

After the conclusion of the actions in the whole of Turkey, 56,569 GWh/a primary energy will be saved. At the same time, 13,992,985 Tons of CO_2 emission will be prevented yearly. The global cost will be reduced by 87,393 million TL in 30 years. In the other word, the application of step-by-step scenarios for related buildings in the whole of Turkey will lead to 2,913 million TL yearly direct profit for the country. The amount of indirect profit of energy retrofit provided by unemployment rate reduction, investment opportunity creation, and so on should be calculated to define the exact amount of profit for the country.

Whole electricity and natural gas consumption in the housing sector of Turkey were 46,189.7 GWh (TÜİK, 2016) and 9,304.42 million m^3 (T.C. Enerji Piyasasi Düzenleme Kurumu, 2015) in 2014. It is equal to about 206,724 GWh primary energy. Thus, it is possible to reduce about 25% of primary energy consumption related to electricity and natural gas consumption in Turkey by application of the step-by-step scenarios.

6. CONCLUSIONS

The current state on improving energy performance of buildings is far away from EU targets both in the EU member and associate states as the renovation rates still is too low with about half of the target. One of the main barriers against deep renovation of existing buildings is deficiencies in the financial resources. This study is trying to compete with this barrier by encouraging the flat owners to involve in their actions as financiers. As state-of-the-art knowledge related to energy consumption of buildings in Turkey, only very small amount of existing buildings has been renovated with only insulation and after received energy performance certificate (EPC) with energy consumption class C, which is the minimum level that a new building needs to achieve in order to be issued the mandatory EPC. For existing buildings in Turkey, there are not many actions related to improving their energy performance. The most common renovation action is implementation of insulation, as it is the only option that a financial solution exists for, while it is not sufficient. The insulation improvements can just reduce a small portion of energy consumption and sometimes it is harmfull as it can increase the cooling energy consumption especially in the buildings with high internal gains.

The current study is aimed to introduce an approach to increase the applicability of the retrofit actions. In this way, the study presented a sample process through the appropriate global cost calculation method for the development of national cost optimality methodologies that take into consideration local market conditions. Also, the adaptation process of cost-optimal calculation methods for one step and step-by-step retrofit were analyzed through six detached and row residential buildings, which were defined as national reference buildings. The buildings have the same geometry but involved different envelope properties which have designed according to Turkish standards. The buildings were located in three different climates in Turkey. The results of this study illustrated that existing buildings' retrofits have significant impact on the national energy consumption and economy.

As one of the significant barriers in the national market resulted from the reduction in owners' contribution, the methodology was adopted from the Recast-EPBD, and the results were thoroughly analyzed to define the optimum retrofit measures with reasonable initial investment cost to encourage owners to become involved in the retrofit actions. The aim of the study was to determine a solution by which the effective and optimum measures of conducting energy-efficient retrofits of detached and row residential apartment buildings could be performed and that buildings' owners are encouraged to be self-finance their retrofit projects. Thus, a reasonable amount that the owners could be expected to invest was determined in accordance with some national statistics. Then, different retrofit measures were defined and applied to the case buildings. The cost calculation was based on the EN standard by considering national conditions. The payback period, primary energy consumption, and CO_2 emission of each measure involved in the case were calculated, and a global cost vs. PEC graph was constructed. The amount that each owner should be expected to contribute was determined according to this information. It was important that thorough analysis was conducted to prevent any unforeseen mistakes during the retrofit process. In addition to the initial investment cost, global cost, and energy consumption, payback period also plays a significant role in determining the feasibility and effectiveness of any retrofit measures.

In all three case studies, it was possible to define the optimum retrofit measures according to the established methodology. However, due to the investment costs, none of the optimum combined actions should be carried out as a single retrofit project. Instead, it is clear that any retrofit action should be implemented in at least five stages to increase the possibility of owners' acceptance. In this case the amount of investment cost would be reasonable amount to be paid by flat owners, hence, the hypothesis of the study is verified.

The work produced in this thesis represents the first attempt at developing a methodology for step-by-step retrofit to increase the yearly retrofit rate and make them enthusiastic for owners. Such a methodology is focused on defining the cost optimum measures and then divide them into some stages to apply. Each of stages should have acceptable cost for owners.

The result of the study related to the energy efficient retrofit of the existing detached and row residential buildings in the cold climate of Turkey entails that buildings in this

region should be given priority over those that are located in the mild and hot-humid climates. This approach would provide more energy and global cost savings for the country as the average primary energy saving in this climate is 98.8 kWh/m^2.a while it is 89 and 76.4 kWh/m^2.a for hot-humid and mild climate respectively. The average amount of global cost saving in cold climate is 172.8 TL/m^2 while it is 156.4 and 131 TL/m^2 for hot-humid and mild climate respectively.

Also, the results of this study indicate that, even without high-tech improvements in the energy systems of a building, it is possible to achieve a primary energy saving more than 50% and global cost more than 20% in Turkish residential buildings. These scenarios can reduce CO_2 emission by more than 50%. All of these retrofit actions have less or equal to 10-years payback period. Such an action has at least about 9500 TL initial investment cost per flat. This cost is very high amount compared to the yearly income of households when applied in one step. It requires a huge financial support to meet, so it cannot be acceptable for most of the Turkish flat owners. Thus, to make them feasible and applicable, it is necessary to use multi-step scenarios. By such scenarios, it is possible to reduce the initial investment cost to about 2270 TL per year per flat during the application process. Based on national statistics for average household income, it can be reasonable amount for yearly payments. In this case the amount of primary energy, global cost and CO_2 emission savings will be more than about 47%, 20% and 45% respectively. The amounts of reduction in these savings are negligible when compare with the benefits arise from increasement in the yearly retrofit rate at the national level.

To be more clear, as it takes some years to conclude such a project, the amount of benefits and savings in a project will be reduced. On the contrary, it will increase the amount of yearly retrofit actions at the national level, so the benefits provided by such an action would be increased in the large scale. It means that one of the significant barriers that is resulted from households' budget deficiencies, will be removed by this method, and the retrofit rate will be increased so the country based benefits will be increased. For example, one step application provides at least 54%, 22.9% and 53% of primary energy, global cost and CO_2 emission saving respectively for the case study buildings while by application of step-by-step retrofit, these amounts for a building will be reduced to about 47%, 21% and 44%. But, it is anticipated that the retrofit rate in the national level will increase from about 1% to 3% by application of step-by-step

retrofit. In this case, the amount of yearly PEC saving will increase from about 650 GWh to 1,697 GWh per year and the amount of CO_2 emission saving will increase from 165,777 Tones to 419,789 Tones per year. This is a huge profit for the country.

Additionally, results of this study are indicating that the total primary energy saving potential is 56,569 GWh in Turkey. It is about 25% of whole primary energy consumption related to electricity and natural gas consumption in the housing sector in Turkey in 2014. Although, the exact result can be revealed when similar analyses have been done on all of the reference buildings. Also, it is necessary to perform a rigorous investigation about occupants' behavior and user profile. Different user profile should be applied in the future studies.

The result of this study can be used in the local energy planning and are very crucial from energy policy planning point of view. It is necessary to conduct similar researches and studies to provide a concrete base for an urban and district energy planning.

To have the advanced results, it is necessary to support the analyses by further studies including more buildings' type. Also further targets can be implemented in the studies. For example, similar methodology can be applied to retrofits through nearly zero energy buildings rather than cost-optimal level. The most common retrofit measures can be insufficient to reach higher energy performance in all kind of the buildings located in the different climatic regions. Advanced improvements in the energy systems of the buildings would be required to reduce the energy consumption sufficiently. This kind of retrofit measures are usually very expensive but should be investigated through step-by-step retrofit to be acceptable for owners.

To improve the accuracy of cost optimal and step-by-step analyzes related to energy retrofit of the existing buildings at the national level, the rigorous calculation needs to be carried out to investigate the effects cost-optimality and step-by-step retrofit on all of the reference buildings in Turkey. At the meantime, cost-optimality analyzes have been done for just some of the 26 reference Turkish buildings while step-by-step analyses have been done for just two of them. It is necessary to apply these analyzes on all of those buildings to make an accurate perception in national level. Indeed, more studies need to be carried out to establish the proper scenarios across different climates and building types. Further studies considering more residential buildings' types could also lead to the establishment of benchmarks for performance and the setting of minimum standards. Such studies could include a different insulation material, glazing

systems, high-tech façade systems, lighting scenarios, shading devices, automation systems, renewable energy systems, and so on.

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