ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

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Ph.D. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

BELİRSİZLİK DURUMLARINDA TRİJENERASYON SİSTEMLERİNİN PLANLANMASI VE STOKASTİK DEĞERLENDİRİLMESİ

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MAYIS 2019

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To my spouse and children,

FOREWORD

Generally centralized power generation approaches are characterized by high rates of energy losses due to waste heat and distribution inefficiencies. Therefore, auto-production enables a more efficient energy usage thanks to the elimination of the losses that stem from the distribution system of energy plants. Accordingly, Combined Cooling Heat and Power (CCHP) systems are the most well-known technologies for efficient energy usage since they are built as decentralized systems, and they are operated close to where it is needed.

Nevertheless, It is not an easy decision for investors to invest in CCHP systems. Decisions for investments are generally taken by the conventional method, which relies on the result of an economic analysis with the assumption that variables will remain stable over the time the analysis is made. However, this kind of systems is dynamic and all the parameters are subject to change until the day the CCHP system expires economically. Thereby, CCHP systems work under uncertainty conditions during their economic life. The methods and evaluations proposed in this thesis provide a broader point of view to decision makers during the CCHP planning by providing all the possible risks at the stage of design and economic analysis for systems with uncertainties.

This thesis becomes a reality with the kind support of many individuals. First I would like to express my sincere gratitude to my advisor, Prof. Dr. Üner ÇOLAK, who provided strong support and encouragement throughout of the study. His confidence in me was essential to the completion of this work. Next I would like to thank Prof. Dr. Gülgün KAYAKUTLU as well for her guidance and insight throughout the research.

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ABBREVIATIONS

CHP	: Combined Heat and Power
CCHP	: Combined Cooling Heat and Power
AB	: Auxiliary Boiler
AC	: Absorption Chiller
ED	: Energy Demand
EP	: Energy Price
HRS	: Heat Recovery System
HTM	: Historical Trend Method
LCV	: Lower Calorific Value
MC	: Mechanical Chiller
MCM	: Monte Carlo Method
NGC	: Natural Gas Consumption
PDF	: Probability Density Function
PGU	: Power Generation Unit
PM	: Parametric Method
PP	: Payback Period
SM	: Scenario-based Method
SME	: Small and Medium size Enterprises
SP	: Separate Production
COP	: Coefficient of Performance
OC	: Operational Cost
DPP	: Discounted Pay-back Period
NPV	: Net Present Value
B/C	: Benefit/Cost
FEL	: Following Electricity Load
FTL	: Following Heat Load
GA	: Genetic Algorithms
GM	: Gas Motors
IC	: Influence Coefficient

SYMBOLS

b	: Slope of regression
a	: Regression constant
tns	: Total number of scenario
n	: Years
J	: Number of Simulation
μ	: Average
α	: Shape factor
β	: Shape factor
$\triangle$	: Change in variable
δ_{smc}	: Specific maintenance cost per hour [USD]
η_{ab}	: Auxiliary boiler efficiency
η_{pgu}	: PGU efficiency
η_{hrs}	: Heat Recovery System efficiency
σ	: Standard deviation
E_d	: Electricity demand [kW]
Q_d	: Heating demand [kW]
R_d	: Cooling demand [kW]
Q_r	: Driving heat for absorption system [kWh
Q_c	: Heating power of PGU [kWh]
awh	: Annual working hours of the plant
amc	: Annual maintenance cost
P_{ep}	: Electricity price [USD/kWh]
P_{fa}	: AB fuel price
W_{pgu}	: Generated electricity by PGU
R_q	: Cooling capacity of absorption chiller[kWh]
COP_{ac}	: Coefficient of performance of AC
COP_{mc}	: Coefficient of performance of MC
Q_{ab}	: Heat generated by AB
Q_I	: Waste heat
E_{ac}	: Electricity power needs of AC
E_r	: Electricity power needs of MC
P_{fc}	: Natural Gas price [USD/m^3]
R_e	: Cooling capacity of mechanical chiller[kWh]
tas	: Total annual saving
$Icchp$	: Investment cost of CCHP [USD]
OC_{CCHP}	: Operational cost of CCHP system
θ	: Occurrence probability
OC_{SP}	: Operational cost of separate production
C_{gc}	: Specific gas consumption of PGU

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PLANNING AND STOCHASTIC EVALUATION OF COMBINED COOLING HEAT AND POWER SYSTEMS UNDER UNCERTAINTY

SUMMARY

CCHP (Combined Cooling Heat and Power) systems are the most well-known technologies for efficient energy usage and it usually refers to simultaneous production of cooling, heating and power from a single energy source. CCHP plants are built as decentralized systems, and they are operated close to where it is needed. Thus, CCHP systems are considered as more efficient, profitable, reliable and environmentally friendly systems compared with conventional generating plants. Nonetheless, CCHP systems or any other energy conversion systems should be designed and operated effectively to gain the expected advantages.

It is not an easy decision for a SME (small and medium size enterprises) to invest in CCHP systems. Decisions for investments are generally taken by the conventional method, which relies on the result of an economic analysis with the assumption that variables will remain stable over the time the analysis is made. However, this kind of systems is dynamic and all the parameters are subject to change until the day the CCHP system expires economically. Thereby, CCHP systems work under uncertainty conditions during their economic life. The technical and financial performance of the system is affected by various parameters which include the fluctuation of energy loads, working hours, energy prices, exchange rates and interest rates. Accordingly, evaluating only the scenario where the current values of variables are taken into account may not help investors in decision making owing to uncertainties, the probability of occurrence of uncertainties and their outcomes.

The analysis held in this study has been based on real and current operational data of an existing industrial facility located in Istanbul. Beside that, This study has two stages to assess the uncertainties in CCHP systems.

The main purpose of the first part of the study is to specify a model and a methodology to select the best CCHP scheme in the presence of uncertainties. Differing from previous studies, this study examined the uncertainties in CCHP systems and evaluated the impacts of these uncertainties on the operational decision-making process as well as the stochastic impacts on the decision making process of the given investment.

In the first stage, the system has been evaluated as a sole CHP system in the light of the updated value of the variables, then the system has been designed as a CCHP system by adding the absorption chiller with the intention of covering the cooling demand partly or fully. Setting the correct load capacity and scheduling is important while deciding on whether the most profitable system should be CHP or CCHP for a given plant. For this propose, macro program in Microsoft Excel has been run in order to determine the most proper capacity for the absorption chiller that will maximize the total annual saving. After determining the most proper cooling load of the absorption chiller, the system has been re-evaluated in the economical aspect.

In another subsection, sensitivity analysis has been applied with the purpose of seeing the impact of the variables on the result. Following this, a new formula has been created to analyze and calculate the effects of variables on the result of the objective function on a percentage basis.

Genetic algorithm is used to see the best case scenario in given constrains of uncertain variables. The result of this forms a reference for the comparison of the actual situation with the best case scenario. As a last step, possible results of the total annual saving have been re-calculated by using probabilistic models under non-parametric stochastic method.

The analyses conducted in first stage have specifically addressed the variables that affect the economic feasibility of the investment and the uncertainties that may affect the investment any time in the systems economic life span. The main objective is to analyze all the possibilities and changes of the uncertain parameters during the life of the system to help investors see the possibility of the occurrence of the best and worst case scenario before making investment decision. Moreover, it is shown that some certain criteria should be satisfied in order for CCHP power plants to be more feasible. The results concluded from this stage are mentioned more in details in the last section of the manuscript.

This stage of study has revealed that an evaluation made solely by considering the current values of the variables of the system is not sufficient to analyze the profitability of the investment. Apart from the conventional evaluation, the random changes of the independent variables at any time should be evaluated in order to see how they affect the profitability. Accordingly, it has been concluded that the deterministic evaluation is not sufficient to assess CCHP systems by its own and the stochastic evaluation gives a broader point of view in terms of overseeing all possible risks.

The first stage of the thesis presented a very wide range of possibilities to assess the profitability of the system. At second stage, a re-evaluation was carried out in order to make a clearer analysis considering the historical data of the independent variables that affect the applicability of the system and the correlations between the variables, if any, and the probability density functions of the variables.

Second stage of the study has been aimed to estimate how the profitability of a CCHP system, which is considered investable based on current values, will change throughout its economic life by adopting stochastic methods. Accordingly, the system has been analyzed under four different simulation methods, namely parametric method, historical trend method, Monte Carlo method and scenario-based method, and their results have been compared.

Among all the studied methods, the Monte Carlo and the historical trend methods directly take historical data as a reference. The parametric method, on the other hand, uses only the parameters of the mean and standard deviation from the historical data as a reference and thereafter assumes that all parameters will follow the normal distribution. Differing from these methods, the scenario-based method tries to determine where the objective function will be concentrated by considering all probable scenarios.

In this regard, the parametric method gives results across the widest range, offering an unclear prediction about future results. The Monte Carlo method gives the highest mean value, while the historical trend method gives probabilities in a narrower range.

The scenario-based method, meanwhile, offers a broader prediction than the historical trend method and also predicts a lower mean value for tas.

Second stage of the study has showed that Investments in energy systems, including CCHP systems, face uncertainty. To answer whether an investment will remain profitable in the midst of these uncertainties, different methods can be applied either using past data or considering all possible scenarios. Although each method used in this study has certain advantages and disadvantages, all four methods can be used to evaluate CCHP systems at the investment stage. Since prices in almost all countries, particularly in the energy market, may not move in line with the historical trend, this study has shown that the scenario-based method is most appropriate to adopt given the comparisons and contrasts it provides.

BELİRSİZLİK DURUMLARINDA TRİJENERASYON SİSTEMLERİNİN PLANLANMASI VE STOKASTİK DEĞERLENDİRİLMESİ

ÖZET

Ülkemizde kullanılan enerjinin önemli bir kısmı, orta ölçekli sanayi tesisleri tarafından tüketilmektedir. Bu tesislerin kendi enerjilerini üretmesi, ülkenin enerji politikaları ve cari açığa katkısından dolayı önem arz etmektedir. Bunun sebebi öncelikle enerji nakli sırasında oluşan kayıpların önlenmesi ile Kojenerasyon / Bileşik Isı ve Güç (CHP) ve Trijenerasyon / Bileşik Soğutma, Isı ve Güç (CCHP) sistemleri gibi verimliliği yüksek sistemlerin kullanılabilmesidir.

CHP ve CCHP yatırımları uzun teknik ve ekonomik ömürlere sahiptir. Bu tür yatırımlarda yaşam döngüsü 10 ila 20 yıl arasında değişir. Ancak, bu uzun zaman aralığında, sistemin tasarımı ve planlaması aşamasında kullanılan değişkenlerin sabit kalması veya değişimlerin aynı eğilimde devam etmesi mümkün değildir. Elbette sistem analizi çoğu zaman zaman güncel veriler ışığında yapılır ama yıllar içinde rassal değişimler sistemin ekonomikliğini ve teknik verimliliğini olumlu veya olumsuz yönde etkiler.

Yatırımcı, belirsiz ortamda yatırıma karar vermede çoğu zaman çekimser davranır. Bunun en önemli nedeni, belirsizlikler ve bu belirsizliklerin kurulacak sisteme olan muhtemel etkilerini öngörememesinden kaynaklanır. CCHP sistemleri de, diğer bir çok enerji sistemlerinde olduğu gibi, dinamik sistemlerdir ve tasarım ve planlama aşamasında bir çok belirsizlikler barındırır. Öncelikle bu belirsizliklerin neler olduğu ve sistemin ekonomik analizi üzerine olan etkilerinin tespit edilmesi önem arz etmektedir.

Enerji yatırımlarının önündeki en önemli engel yine enerji fiyatlarındaki belirsizliktir. Ancak yapılan yatırımın avantajlı olması için güncel enerji fiyatlarının bu yatırım için uygun, yatırımın avantajını koruyabilmesi için ise enerji fiyatlarındaki muhtemel değişimin öngörülebilir olması arzu edilir.

Belirsizliklerin ve risklerin olduğu durumlarda karar verme oldukça zordur. Özellikle enerji yatırımlarında, ülkedeki ekonomik ve politik değişimler veya belirsizlikler, yatırım kararı almada çok etkili olmaktadır. Enerji yatırımları için genel olarak üç farklı riskten bahsedilebilir. Bu riskler; tasarım riskleri, teknik riskler ve finansal riskler olarak tanımlanabilir.

CCHP sistemlerinin ekonomik analizleri için genel bir kural yoktur. Sistemin ekonomikliği, tesisin tasarımına, operasyon kriterlerine ve sistem parametrelerinin değişimlerine bağlıdır. Bu değişkenler; enerji talebindeki/yüklerindeki değişimler gibi iç değişkenler veya enerji fiyatları, kurlar, vergiler ve teşvikler gibi dış değişkenler olabilir.

Bu çalışma, enerji yoğun orta ölçekli sanayi tesislerinde uygulanan CCHP gibi oto prodüksiyon sistemlerinin termo-ekonomik analizlerini, optimizasyonunu, yatırıma

karar verme yöntemlerini, belirsizliklerin amaç fonksiyonuna etkilerini, skolastik belirsizliklerin farklı yöntemler ile analizini ve bu yöntemlerin karşılaştırılmasını kapsamaktadır.

Tüm bu aşamalar ile, CCHP yatırımları üzerindeki tüm riskleri değerlendirilebilecek skolastik modeller ortaya konulması hedeflenmiştir. Tez kapsamında yapılan analizlerde, mevcut bir tesis için tasarlanan CCHP sistemine ait gerçek ve güncel veriler kullanılmıştır.

Tez iki aşamadan oluşmaktadır. Genel olarak, birinci aşamada, CCHP yatırımlarındaki tüm riskler ve olası etkileri değerlendirilirken, ikinci aşamada bu risklerin yatırım sonrası dönemdeki muhtemel değişimleri ve bu değişimlerin sistemin karlılığına olabilecek etkileri analiz edilmiştir.

Tezin ilk aşamasında; kurulacak söz konusu sistemin CHP olarak mı yoksa CCHP olarak mı kurulmasının daha avantajlı olacağı sorgulanmıştır. Sistemin CCHP olarak kurulmasının avantajlı olması durumunda, sistemden elde edilecek yıllık tasarrufu maksimize edecek en uygun yük dağılımı deterministtik yöntem kullanarak optimize edilmiş ve bu yüklere göre uygun kapasitede sistem elemanlarının seçimi gerçekleştirilmiştir. Bu aşamada özellikle absorpsiyonlu soğutma kapasitesinin seçimi ve sistemin karlılığına olan etkisi vurgulanmıştır.

Daha sonra, kurulan sistemden elde edilen yıllık tasarrufu etkileyecek değişkenler ve bu değişkenlerin yıllık tasarrufa olan etkileri, hassasiyet analizi kullanılarak belirlenmiştir. Hassasiyet analizi sonucu, her bir değişkenin sistem karlılığına olan etki katsayıları formüle edilerek, yatırımcının sistemin ekonomikliği üzerindeki riskleri daha net görebilmesi sağlanmıştır. Hassasiyet analizi yönteminde Microsoft Macro araçları kullanılmıştır.

Tesisin ihtiyaç duyduğu termal yükler ve dolayısıyla elektrik yükü mevsimsellikten önemli ölçüde etkilenmektedir. Yüklerdeki bu mevsimsel değişimlerden dolayı sistemin karlılığı da değişkenlik gösterir. Karlılık üzerinde bir risk olarak değerlendirilen bu değişimlerin muhtemel etkileri, belirlenen mevsimsel kısıtlar içerisinde, parametrik olmayan rassal değişimler kullanılarak belirlenmiştir. Bu aşamada yıllık tasarrufu maksimize edecek en uygun yük aralıkları yine Macro araçları yardımıyla tespit edilmiştir.

Bir sistemin karlılığını, muhtemel avantaj ve risklerini değerlendirirken, en iyi ve en kötü senaryo durumlarındaki muhtemel kazanç/kayıp limitlerini belirlemek önemlidir. Söz konusu sistemin en iyi senaryo durumu, MS. Excell Genetik Algoritma aracı ile, belirlenmiştir.

Tezin ilk aşamasında son olarak, yıllık tasarruf üzerindeki tüm riskleri ve bu risklerin muhtemel sonuçlarını değerlendirebilecek bir olasılık dağılımı oluşturulmuştur. Bu dağılımın oluşturulmasında parametrik olmayan rassal yöntem kullanılmış, sistemin güncel ve muhtemel kayıp/kazançları değerlendirilmiştir.

Birinci aşamada, yukarıda bahsi geçen tüm değerlendirmeler ile beraber, aşağıdaki sonuçlar özellikle ön plana çıkmıştır;

CCHP sistemlerinin ekonomikliğini etkileyen bir çok belirsiz değişken mevcuttur. Bu değişkenlerden en önemlileri, enerji fiyatları, sistemin yıllık çalışma saati, termal yük talebi değişimleri, döviz kurlarındaki değişimler ve bakım giderleri olarak sayılabilir.

Soğutma ihtiyacı olan her tesis için CCHP sistemi uygulaması doğru bir yaklaşım olmayabilir. CCHP sistemleri özellikle belirli yük aralıklarında karlı olabilir.

Türkiye'deki CCHP yatırımları için döviz kuru seviyesi çok önemli bir parametredir. Genellikle sistem elemanları yurtdışından ithal edildiğinden, yatırım aşamasındaki döviz kuru ve sistemin faaliyete geçtikten sonra oluşabilecek döviz kuru hareketleri sistemin amortismanını ve karlılığını doğrudan etkilemektedir. Yerel para biriminin, yani ülke para birimi TL'nin değer kazanması CCHP yatırımlarını daha cazip hale getirir.

CCHP sistemleri kurulduktan sonra, iyi bir ekonomik geri dönüş arzulanıyor ise, mümkün olan en yüksek zaman periyodunda çalışması gerekmektedir. Yıllık 7.200 h'den az çalışan sistemler ekonomik açıdan uygulanabilir olmaktan uzaktır.

CCHP yatırımının uygulanabilir olup olamayacağını anlayabileceğimiz en kolay kriter, ısı enerjisi fiyatı ile elektrik enerjisi fiyatı arasındaki ilişkidir. Söz konusu kriter, sonuç ve değerlendirme bölümünde detaylı açıklanmıştır.

CCHP sistemlerinde absorbsiyonlu soğutmanın her zaman %100 kapasite kullanımı ekonomik olmayabilir. Güç sistemini ürettiği atık ısı ve tesisin yük ihtiyacına göre absorbsiyonlu soğutma kullanımı optimize edilmelidir. Çalışmadaki vakıa analizinde, soğutma ihtiyacının absorbsiyonlu soğutmadan optimum karşılanma oranı %44 olarak bulunmuştur.

Özellikle Türkiye gibi, yüksek kredi faizi olan ülkelerde, yatırımcılar yatırımlarını değerlendirirken basit geri ödeme süresi yerine, gerçek geri ödeme süresini kullanarak değerlendirmelidirler. Paranın zaman değeri vardır ve yatırımcılar yatırımlarını her zaman kredi kullanarak finanse etmek isterler. Bu çalışmada, CCHP sistemleri için gerçek geri ödeme süresi kriterinin, sistemin yatırımına karar vermedeki önemini ortaya koymuştur.

Çalışmadaki vakıa analizi, parametrik olmayan metot ile değerlendirildiğinde, söz konusu CCHP yatırımının, ekonomik ömrü boyunca, herhangi bir zaman aralığı içinde ve sistemin karlılığı bakımından; en iyi senaryonun gerçekleşme olasılığının %0, en muhtemel yıllık tasarrufun gerçekleşme olasılığının %31 ve yatırım için kritik değer olarak tespit edilen değerin gerçekleşme olasılığının %35 olduğu bulunmuştur. Bu olasılık değerleri, sistemin ilk fizibilitesi olumlu çıkması durumunda bile, parametrelerdeki muhtemel değişimlerin, sistemin ekonomikliğini her zaman sorgulanır ve risk altında tutabileceğini göstermiştir.

Birinci aşamadaki analiz, sistemin karlılığını değerlendirmek için çok geniş bir olasılık aralığı sunmuştur. Dolayısıyla, CCHP sistemleri, yatırım sonrasındaki muhtemel değişimler için, daha farklı ve detaylı şekillerde analiz edilmelidir.

Tezin ikinci aşamasında, CCHP yatırımları tamamlandıktan sonra, sistemin ekonomik ömrü boyunca karlılığına etki edecek belirsizliklerin ve değişkenlerin gelecekte nasıl hareket edebileceklerini öngörmek ve bu belirsizlikler ışığında gelecekle ilgili sistemin ekonomikliği hakkında tahminleme yapmak hedeflenmiştir. Bu bağlamda, daha net bir analiz yapabilmek için, sistemin uygulanabilirliğini etkileyen bağımsız değişkenlere ait tarihsel veriler, var ise bu değişkenler arasındaki korelasyonlar ve değişkenlere ait olasılık yoğunluk fonksiyonları göz önüne alınarak tekrar değerlendirme yapılması öngörülmüştür. Bu aşamada, çalışmanın daha uluslararası ve genel bir analiz sunabilmesi için, yerel para birimi kullanılmamış, dolayısıyla döviz kurlarındaki değişimin etkisi göz ardı edilmiştir.

Tüm bu yeni değerlendirmeler ile söz konusu sistem, Parametric metot, Historical data metot, Monte Carlo metot ve Senaryo bazlı metot olarak 4 farklı yöntem ile irdelenmiş ve sonuçlar karşılaştırılmıştır.

Belirsizlik analizinde ve stokastik metotlarda en önemli adım, belirsizliğin hangi dağılıma göre hareket edeceğinin tespit edilebilmesidir. Doğru dağılımı tespit etmede, geçmiş verilerin analizi önem arz etmekle beraber, gelecek hakkında da öngörüde bulunmak için uzman kişilerin deneyimlerine başvurulabilir. Dolayısıyla doğru dağılıma, bahsi geçen parametreye ait tarihsel veriler ve gelecekle ilgili öngörüler ışığında karar verilmelidir.

Sistem, yıllık tasarruf hedef fonksiyonuna için, yukarıda bahsedilen metotlar ile değerlendirildiğinde, aşağıdaki sonuçlara ulaşılmıştır. Öncelikle tüm metotların sonuçları Normal dağılıma yakın bir olasılık dağılımı vermiştir.

Parametrik metot, hedef fonksiyonda oluşabilecek muhtemel sonuçları en geniş aralıklarda vermiş olup, önümüzdeki yıllara ait sistemden elde edilecek muhtemel avantajlar konusunda çok net olmayan öngörü sunmuştur.

Monte Carlo metodu, yıllık tasarruf için en yüksek ortalama değeri (mean value) vermiştir. Dolayısıyla söz konusu sistemin ileriki yıllarda daha da karlı olabileceği ihtimalini ortaya koymuştur. Bu metotta ortalama değerin yüksek çıkmasının ana sebebi, geçmiş yıllardaki veriler ile oluşturulan elektrik ve doğal gaz fiyatlarına ait olasılık dağılımlarının BETA dağılımına uygun bir dağılım ortaya koymasıdır. Bu dağılıma göre, her hangi bir zaman aralığı içinde, elektrik fiyatlarının artış yönünde, doğal gaz fiyatlarının ise azalış yönünde hareket edeceği öngörülebilir. Bu durum CCHP sistemlerinin karlılığı açısında olumlu bir sonuç vermektedir.

Historical Trend metodu, sistemin karlılığı açısından, diğer metotlara göre daha dar aralıkta bir sonuç vermiştir. Muhtemel ortalama değer öngörüsü olarak ise Monte Carlo metodundan sonraki en yüksek ortalama değeri vermiştir. Bu metotta, enerji fiyatları için doğrusal regresyon analizi uygulanmış ve gelecekte enerji fiyatlarının bu trende uygun hareket edeceği ön görülmüştür.

Senaryo bazlı metod ise, Monte Carlo ve Historical Trend metotlarına göre daha geniş bir öngörü aralığı sunmuş ancak gerçekleşebilecek en muhtemel ortalama değer olarak ise Parametrik metota yakın bir sonuç vermiştir.

Bu değerlendirmeler ile beraber, ortaya çıkan sonuçlar; kritik seviye, güven aralığı ve varyans analizi olarak üç farklı kriter ile de değerlendirmeye tabi tutulmuştur.

Sistemin karlılığı için belirlenen kritik değerin üzerinde bir yıllık tasarruf verme olasılığı; parametrik metoduna göre %69.8, Monte Carlo metoduna göre %91.2, Historical trend metoduna göre %99.3 ve Senaryo bazlı metoda göre ise %71,4 olarak bulunmuştur.

CCHP sisteminden sağlanacak muhtemel yıllık tasarruf %90 güven aralığında değerlendirildiğinde; %90 ihtimal ile parametrik metotta $49,767, Monter Carlo metodunda $145,440, Historical trend metotunda $167,563 ve Senaryo bazlı metotda ise $98,957'in üzerinde gerçekleşeceği tespit edilmiştir.

Sistem varyans metodu ile değerlendirildiğinde ise; Historicak trend ve Senaryo bazlı metot $100k ile $200k arasında daha az volatil/oynak olduğu, Monte Carlo metodunun ise $200k üzerinde daha az volatil/oynak olduğu görülmüştür. Parametrik metot ise tüm aralıklarda daha homojen bir volatilite/oynaklık göstermiştir.

Tüm bu sonuçların ışığında aşağıdaki değerlendirmeler yapılabilir. CCHP sistemlerinin yatırımları kendi içinde bir çok belirsizlikler barındırmaktadır. Bu belirsizlikler dolayısıyla, yatırımı yapılan sistemin karlılığının devam edip edemeyeceği önemli bir sorudur. Bu sorunun cevabını alabilmek için geçmiş verilerden faydalanılan veya tüm olası senaryoların hesaba katıldığı farklı metotlar uygulanabilir. Bu metotlar içerisinde, Parametrik, Monte Carlo ve Historical trend metodu geçmiş yıllardaki verileri doğrudan referans alarak, Senaryo bazlı metod ise, tüm belirsiz parametrelerin, olası tüm farklı senaryolara göre nasıl hareket edebileceği değerlendirilerek uygulanır.

Bu sonuçlara göre, söz konusu metotların hangisinin uygulamada tercih edileceği, eldeki tarihi veri setinin ne kadar kapsamlı olduğuna, bu verilerin doğruluğuna, karar vericinin deneyimlerine ve değişkenlerin kendi aralarındaki etkileşimlerine/korelasyonlarına bağlıdır. Bunlarla beraber, bu belirsiz değişkenler için belirlenen kısıtların limitleri, bu kısıtların sürekli veya kesikli olmaları ve değişkenlerin bu kısıtları aşma potansiyelleri model belirlemede oldukça önemli olduğu sonucuna ulaşılmıştır.

Bu bağlamda, yeterli tarihsel verinin olması durumunda Parametrik metodun, daha detaylı tarihsel verilerin olması durumunda Monta Carlo metodunun, tarihsel trendlerin çok volatil/oynak olmayıp daha doğrusal olması durumlarında ise Historical trend metotlarının kullanılmasının daha uygun olacağı görülmüştür. Senaryo bazlı metot ise, hesaplamada tüm riskleri göz önüne alması özelliği ile, her durumda baş vurulması gereken önemli bir metot olduğu sonucuna ulaşılmıştır.

Bu çalışmada bahsi geçen her bir metodun uygulamada öne çıkan bazı avantajları ve dezavantajları olmasına rağmen, yatırım aşamasındaki CCHP sistemlerinin değerlendirilmesi için kullanılabilecekleri sonucuna ulaşılmıştır. Bir çok durumda ve hemen her ülkede, özellikle enerji fiyatları söz konusu olduğunda, fiyat değişimlerinin tarihsel trendlerin dışında hareket etme ihtimalleri söz konusu olabilmektedir. Bu tür durumlar için, diğer metotlar ile birlikte, Senaryo bazlı metodun kullanılmasının, kıyaslama ve karşılaştırma açısından uygun olacağı değerlendirilmiştir.

Bu çalışma, farklı alanlarda uygulanan çeşitli analiz yöntemlerini bir araya getirerek, CCHP sistemlerinin termo-ekonomik ve belirsizlikler açısından daha detaylı değerlendirilmesi konusunda farklı bir bakış açısı sunmuştur. Bu bağlamda, CCHP sistemlerine ait tüm belirsizliklerinin, sistemin ekonomikliğine ve amortismanına olan muhtemel etkileri ve riskleri her yönüyle detaylı şekilde ortaya konulmuş, bu sayede karar vericilerin en uygun kararı verilebilmesi için kapsamlı bir metodoloji oluşturulmuştur. Bu bakış açısının, CCHP sistemlerinin yanı sıra, diğer tüm enerji yatırımlarının fizibilite aşamasında da uygulanabilir olduğu ve bu sayede ülkemizde sıkça karşılaştığımız yanlış yatırım kararı verme problemine de katkı sağlayacağı öngörülmektedir.

xxx

1. INTRODUCTION

The limitations of energy sources entail a more efficient and economic usage of energy today. Generally centralized power generation approaches are characterized by high rates of energy losses due to waste heat and distribution inefficiencies [1]. Auto-production enables more efficient energy usage by eliminating losses that stem from the distribution system of energy plants [2]. Accordingly, CCHP (Combined Cooling, Heat, and Power) systems are the best-known technology for efficient energy usage, usually referring to the simultaneous production of cooling, heating, and power from a single energy source. CCHP plants are built as decentralized systems and are operated close to where they are needed. Thus, CCHP systems are considered to be more efficient, profitable, reliable, and environmentally friendly than conventional generating plants [3, 4].

Nevertheless, CCHP systems or any other energy conversion systems should be designed and operated effectively to gain the expected advantages. However, It is not an easy decision for investors to invest in CCHP systems. Decisions for investments are generally taken by the conventional method, which relies on the result of an economic analysis with the assumption that variables will remain stable over the time the analysis is made. However, this kind of systems is dynamic and all the parameters are subject to change until the day the CCHP system expires economically. Thereby, CCHP systems work under uncertainty conditions during their economic life.

The technical and financial performance of the system is affected by various parameters which include the fluctuation of energy loads, run-time of the system, energy prices, exchange rates and interest rates and so on. Accordingly, evaluating only the scenario where the current values of variables are taken into account may not help investors in decision making owing to uncertainties, the probability of occurrence of uncertainties and their outcomes. Therefore, all uncertainties and risks should be evaluated in feasibility stage of the investment.

1.1 Purpose of Thesis

This study has two stages to assess the uncertainties in CCHP systems. The main purpose of the first stage is to specify a model and a methodology to select the best CCHP scheme in the presence of uncertainties. Differing from previous studies, this study examined the uncertainties in CCHP systems and evaluated the impacts of these uncertainties on the operational decision-making process as well as the stochastic impacts on the decision making process of the given investment. The proposed methodology helps decision makers see all the possible risks that impact the amortization of the system. After evaluating these risks, it is up to investors decision to undertake or cancel the investment.

Expanding the previous stage further, the main purpose of the second stage is to analyze whether the current feasibility of the CCHP system in the investment stage will persist or not throughout its economic life by using stochastic methods. In other words, the author aims to explain how the uncertain parameters that will have an impact on the profitability of the system during its economic life will unfold over time and to forecast the profitability of the system in the future in the light of these uncertainties.

1.2 Literature Review

There are many studies of CCHP systems, some of which focus on optimization in the design and operation stages, while others involve simulation models or selection approaches and planning solutions, as discussed below with related references.

As it is the case in other energy conversion systems, CCHP systems should be designed and operated efficiently to be able to gain the expected advantages, which is clearly an issue to be discussed under optimization. “Design optimization implies the technical specifications and the properties of substances at nominal loads, while operational optimization finds parameters related to desirable operational regimes" [5]. The optimization of CCHP systems is a complex task since there are many factors and variables involved. Currently, there are several techniques available for the optimization of CCHP systems such as linear programming, non-linear programming, mixed-integer programming and mixed-integer nonlinear programming.

There are many studies concerning CCHP optimization [6] and multi-criteria decision making methods [7, 8]. These studies generally encompass the steps of design and operation. Several studies use linear programming to optimize CCHP systems [9, 10]. Kong at al. [9] presented a simple linear programming model to determine the optimal strategies that minimize the overall cost of energy for the CCHP system. They showed that the optimal operation of the system is dependent upon load conditions. They also concluded that to operate the CCHP system may not be optimal, especially when the electricity-to-gas cost ratio is very low.

Lozano et al. [11] used a simple linear programming model to minimize the variable operational cost of a CCHP system. Similarly, Unal and Ersoz [12], proposed the same model to minimize the total annual variable operational cost and the maintenance cost of a generic CCHP system. The results showed that CCHP systems reduce total annual costs for all operational cases, with the system driven by a gas engine having better performance than the one driven by a gas turbine. Additionally, linear programming was used for the sizing and operational optimization of CCHP in [13]. In [14], mixed integer linear programming was used to plan the short-term operation of CCHP systems. Moreover, several detailed simulation models were proposed in [15].

Ren et al. [16] also developed a linear programming model for the design and evaluation of a biomass energy system. They elaborated sensitivity analyses to show how the optimal solutions would vary due to changes of some key parameters such as electricity and city gas tariffs, biogas price and etc.

Arosio et al. [17] developed and implemented a model for automatic optimization of the operating policy of trigenerative plants. The constitutive equations which formalize the relationships between the plant components and energetic and economic target functions are expressed using linear terms only. The implemented optimization study can be a useful instrument for designers and stakeholders of trigenerative plants.

Cardona [18, 19] investigated the operation and long term planning of the CHCP plant supplying the Malpensa 2000 international airport, by means of profit-oriented linear optimization. They stated that purely profit-oriented management could significantly reduce the annual energy saving; however slight changes in the operational mode allowed to achieve near optimal economic results in respect of the objective for a reduction of energy consumption and pollutant emissions.

Li et al. [20] employed the weighting method and fuzzy optimum selection theory to evaluate the integrated performance of CCHP systems using various operational strategies. Cho et al. [21] summarized the methods used to perform energetic and exergetic analyses, system optimization, performance improvement studies, and the development and analysis of CCHP systems. Another review work [4] classified different types of CCHP systems based on the prime mover, size, and energy sequence usage, suggesting a general approach to select the appropriate CCHP system depending on specific needs. As in CCHP systems, Carpaneto and Chicco [22] specified the models and analyses to select the best CHP planning solution in the presence of uncertainties on a long-term timescale. Their study illustrated and discussed various technological alternatives operated under different control strategies.

The control strategy of a system plays a crucial role in optimization. As in CHP systems, CCHP systems can be operated under one of the following control strategies: on-off operation, FEL (following electricity load), and FTL (following heat load) [1, 23]. With respect to these control strategies, [24] demonstrated that different seasonal load conditions and energy prices result in a reduction in total daily cost from 8% to around 100% in total daily cost. Apart from control strategies, component optimization is also important in overall optimization; however, the optimization of the whole system is a better solution than optimizing only the components [25].

Apart from the deterministic optimization method adopted in the studies mentioned above, stochastic optimization has also been performed. For example, [26] proposed a stochastic, multi-objective model to optimize CCHP operation strategy. Gomez-Villalva and Ramos [27] presented multi-objective stochastic optimization models to manage the energy of industrial consumers in liberalized energy markets. To analyze the risk that stems from energy price uncertainty, they developed a two-stage stochastic program by improving a deterministic optimization model.

In another example of stochastic optimization, Wang [28] proposed an improved multi-objective particle swarm optimization algorithm, which turned out to be effective in dealing with the CHP dispatch problem. Alipour et al. [29] also worked to solve a scheduling problem of CHP systems experienced by an industrial customer using a stochastic programming framework, where an auto-regressive, integrated moving-average technique was used to generate scenarios for electricity price and customer demand. Zhou et al. [30] proposed a two-stage stochastic programming model for the optimal design of distributed energy systems. To solve the optimization problem, they decomposed a two-stage strategy: a genetic algorithm conducted the first-stage search, while the Monte Carlo method handled uncertainty in the second stage.

A probabilistic model was proposed by Zamani et al. [31] for the optimal electrical/thermal scheduling of a virtual power plant to participate in both energy and spinning reserve markets. In that work, a simultaneous energy and reserve scheduling method was presented in light of demand-response programs. Meanwhile, Smith et al. [32] analyzed a CCHP system model under different operating strategies in terms of input and uncertainty. They revealed the significance of conducting uncertainty and sensitivity analyses in predicting CCHP system performance through a case study of a small office building. The uncertainties in the model predictions of primary energy consumption, operational cost, and carbon dioxide emissions were studied in particular.

1.3 Uncertainties and Decision making

Decision-making under uncertainty is an essential, but not an easy task. That is why the decision maker needs to be assisted by tangible instruments for assessing the effectiveness of the alternatives considered. Rather than relying on a deterministic analysis, a probabilistic analysis may pave the way for a better evaluation of the system under uncertainties.

CHP systems can be planned in small-scale uncertainty [33] or large-scale uncertainty [22] depending on the magnitude of the uncertainty. CCHP systems can also be evaluated in the same manner. CCHP systems bear many variables and uncertainties in the phases of investment and operation. The basic variables of CCHP systems to be considered in the decision-making process are like the following: capital cost (investment cost); gas price (e.g., natural gas) used for production of heat and electricity; electricity price provided by the Electricity Distribution System, annual working hours of the system, exchange rate, electricity, heating and cooling load of the plant, annual operation and maintenance cost of the system, interest rate and economic life of the system.

All of the variable's possible values in the future pose an uncertainty. Various tools are generally used while making decisions in such uncertain conditions. Thereby, risk analysis is a useful tool for decision-makers in the midst of many uncertainties to be tackled [34]. Applying probability distributions can be considered as another tool for a healthier evaluation under uncertainty. In [35], goodness-of-fit analysis is used to evaluate the residential load patterns. However, if the exact distribution cannot be derived from the historical data, the normal distribution is assumed as a good first approximation. Therefore, probabilistic models is a technique used to understand the impact of risk and uncertainty in several forecasting models.

The impact of the variables on the objective function reveals the importance of each variable. In this regard, sensitivity analysis is considered as one of the best techniques to evaluate the variables. Sensitivity analysis is a method that determines the level of impact of input(s) on the selected output(s) [36]. It can be used for several reasons [37]: (1) the definition of the inputs which affect the outputs, (2) the rank of the inputs in order of importance, (3) reducing the number of inputs, (4) model tuning. When sensitivity analysis is conducted, several methods are used, one of which is called as the local method. The local method is considered as an easy and one-at-a-time sensitivity measure. The main rule is to change one parameter at a time while keeping the others fixed. Local techniques can be used if there is a linear correlation between inputs and outputs to define the singular effect of selected input parameters on the calculated performance indicator [38]. Li [39] studied the influence of variable energy demands on the performance of CCHP system with sensitivity analysis.

In system analysis, optimization theories are considered in order to minimize, maximize the objective function or reach the given target. Genetic algorithms (GAs) are an optimization technique based on natural genetics developed by Holland [40]. GAs can handle objective functions of any complexity with both discrete (e.g., integer) and continuous variables. GA was applied in [41] for the operation optimization of a CHP system, which supplies a process plant with electricity and steam at various pressure levels. It is proved to be a successful and robust optimization technique, for the optimization of a CHP system.

Unlike the technical analyses mentioned above, another important criterion to evaluate the investment is to conduct economic analysis. Investors and engineers need tools to make wise economic decisions in order to accept or reject project. Thermo-economic analysis, which is the combination of technical and economical aspects, entails many approaches for the cost assessment of simple CCHP systems [42]. Exergoeconomic analysis also deals with the technical optimization, which combines exergy to evaluate and optimize the systems economically [43]. Some theoretical guidelines for the design and operation of practical CCHP plants have been proposed in [44] by using finite time exergoeconomic method. In terms of methods for economic analysis, Biezma and San Cristobal [45] categorized many various methods of project evaluation into four main types: worth methods, rate of return methods, ratio methods and payback methods. Investment cost is one of the main items of economic analysis, which involves the selection of an accurate PGU and an absorption system for the given plant. In the selection of PGU, there are four main factors to watch including the capacity, thermal and electricity efficiency and the specific gas consumption of the system. When the selection of absorption chillers (AC) is concerned; minimum temperature required for the plant, driven heat needed for the AC, efficiency, run time period and the availability of the system are considered crucial.

Considering the above literature review, this study puts forth that investments are subject to long-term uncertainties in their economic life span. All the variables that affect the feasibility of the investment have been simulated with the probabilistic technique with the assumption that all the variables change as per normal distribution. In terms of the techniques for economic analysis, pay-back period method (PP), discounted pay-back period method (DPP), net present value method (NPV) and benefit/cost method (B/C) have been evaluated. In addition, the impact of the variables on the objective function has been assessed with the local method of sensitivity analysis. In this study, the sensitivity analysis has been used in order to determine which variables are required for the probabilistic method. In the light of these evaluations, this study provides an authentic and different point of view to make a better assessment of CCHP systems in the investment level.

2. MATERIALS AND METHODS

2.1 CCHP Systems

Combined Heat and Power (CHP) and Combined Cooling Heat and Power (CCHP) systems are the most well-known technologies for efficient energy usage. CHP system produces electricity and heat simultaneously, which generates electricity and useful heat by using a power station. CHP, therefore, offers energy saving of up to 40% compared to the conventional systems where electricity is generated by power stations and heat by boilers. Apart from electricity and heat, which are generated in CHP systems, CCHP systems can also produce cooling from the same energy source. Consequently, CCHP systems are considered as an extension of CHP systems. In a CCHP plant, heating and cooling systems are driven by the waste energy of a power generation unit (PGU), which renders CCHP systems more efficient. The cooling part of CCHP systems is referred in many studies as absorption groups that are generally fed by CHP thermal energy. Moreover, the scope of CCHP systems can be extended to include conventional electric chillers, heat pumps or direct-fired absorption chillers [46].

A CCHP system is actually an extension of a CHP system, that is, the production of a threefold energy vector requested by the user from a unique source of fuel [46, 47]. In other words,the CCHP system is the form of the CHP system coupled with a heat driven refrigeration system (e.g., absorption chiller) that produces cooling when needed.

The cogenerated heat is also used for regular heating demand. When the recovered heat is less than the heat requirement, the remainder of the heat requirement is met by auxiliary boilers. Mechanical chillers, auxiliary boilers and the connection between the CCHP system and the electricity grid also decrease the risk of shortage and enhance the reliability of the system. In some cases, depending on the legal regulations excess

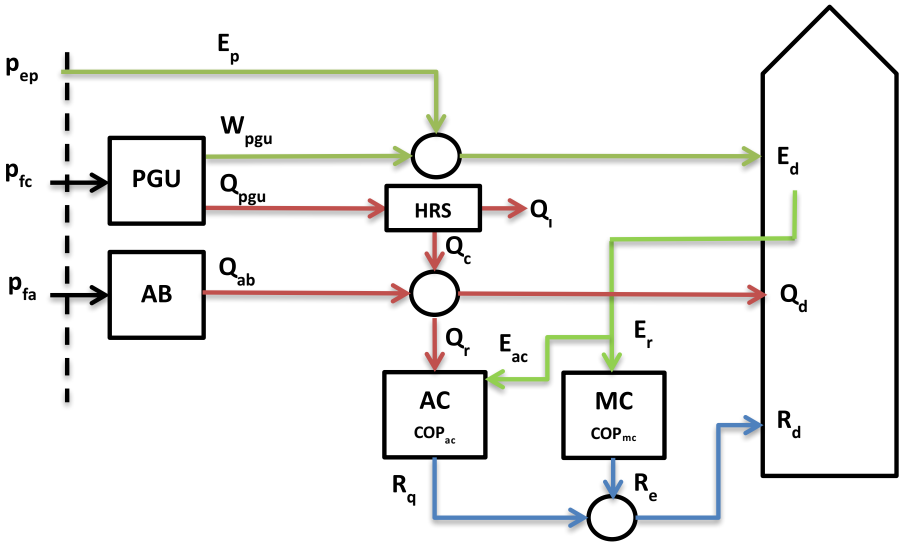

Figure 2.1 : CCHP System.

heat or electricity, if any, can be sold to the grid, or both the excess heat and electricity are allowed to be discharged easily with no cost [48, 49].

The system considered being implemented in the plant is depicted in Fig.2.1. As it is the case in all CCHP systems, this one consists of a PGU, a heat recovery system (HRS), auxiliary boiler (AB) fed by natural gas for regulating heat demand, absorption chiller (AC) and a mechanical chiller (MC).

Simply, the system works as follows: The PGU generates heat and electricity simultaneously. The generated electricity is used to feed the electricity demand of the plant in which the electricity requirement of mechanical chillers is included. The heat generated by the PGU is used for regular heating demand of the plant and the rest of the heat is allocated to absorption chillers. The heat used in absorption chillers must be unused heat in plant's demand. Otherwise, the system may not be efficient. The generated heat is preferably used first in heating demand. What lies behind this is that the usage of the PGU-generated-heat in heating demand is always more efficient than its usage in the AC. This is because the coefficient of performance of the AC (COP_{ac}) is generally lower. The purpose of the AB is to generate heat just for regular heating demand, in case PGU does not generate enough heat. Cooling demand of the plant can be covered either by absorption chillers, by mechanical chillers or by both considering the efficiency of the design.

Total annual saving (tas) formulated in Eq.(2.1) generally can be described as the difference between the total annual operational cost of separate production (OC_{SP}) and the total annual operational cost after building a CCHP system (OC_{CCHP}). In other words, it is simply the difference in the energy cost before and after building a CCHP system.

$$tas = OC_{SP} - OC_{CCHP} \tag{2.1}$$

The operational cost of separate production in an hour can be formulated as in Eq. (2.2)

$$OC_{SP} = E_d.P_{ep} + E_r.P_{ep} + NGC_{ab}.P_{fa} \tag{2.2}$$

In separate production, all cooling demand is covered by an MC, so R_d=R_e. Electricity consumption for an MC can be formulated as in Eq. (2.3).

$$E_r = \frac{R_e}{COP_{mc}} \tag{2.3}$$

The AB, which generates heat to meet heating demand and its natural gas consumption are respectively formulated as in Eqs. (2.4) and Eq. (2.5).

$$Q_{ab} = \frac{Q_d}{\eta_{ab}} \tag{2.4}$$

$$NGC_{ab} = Q_{ab}\frac{860}{LCV} \tag{2.5}$$

The constant number 860 used in the equations is the conversion coefficient between $kcal$ and kWh ($1kWh$ is equal to 860 $kcal$).

Eq. (2.2) can be expanded as Eq. (2.6).

$$OC_{SP} = E_d.P_{ep} + \frac{R_e}{COP_{mc}}.P_{ep} + \frac{Q_d}{\eta_{ab}}\frac{860}{LCV}.P_{fa} \tag{2.6}$$

The operational cost of CCHP systems in an hour can be formulated as in Eq.(2.7). δ_{smc} is the specific maintenance cost per hour, including all maintenance costs for the PGU, AB, MC, and AC.

$$OC_{CCHP} = NGC_{pgu}.P_{fc} + E_p.P_{ep} + NGC_{ab,cchp}.P_{fa} + \delta_{smc} \tag{2.7}$$

The natural gas consumption of the PGU and electricity required from the grid beyond that generated by the PGU are respectively formulated as in Eqs. (2.8) and (2.9).

$$NGC_{pgu} = W_{pgu}.\eta_{pgu}.C_{gc} \tag{2.8}$$

$$E_p = E_d - (W_{pgu}.\eta_{pgu}) + E_r + E_{ac} \tag{2.9}$$

E_{ac} refers to the electricity required by the AC. The natural gas consumption and the capacity of the AB after the CCHP is built are respectively formulated as in Eqs.(2.10) and (2.11). The usable heat of the system after adding the HRS is formulated as in Eq. (2.12).

$$NGC_{ab,cchp} = Q_{ab,cchp}\frac{860}{LCV} \tag{2.10}$$

$$Q_{ab,cchp} = \frac{Q_d + Q_r - Q_c}{\eta_{ab}} \tag{2.11}$$

$$Q_c = Q_{pgu}.\eta_{hrs} \tag{2.12}$$

R_q represents the cooling produced by the AC, formulated as in Eq. (2.13), where Q_r is the heat used in the ACs. COP_{ac} and COP_{mc} refer to the coefficients of performance of the AC and MC, respectively. The plant's cooling demand is the sum of the AC and MC capacity, as in Eq. (2.14) in the case of working together.

$$R_q = Q_r.COP_{ac} \tag{2.13}$$

$$R_d = R_q + R_e \tag{2.14}$$

In Fig.2.1 P_{fa} refers to the fuel of the AB. In this system the AB is fed by natural gas, like the PGU, to regulate heat demand. Accordingly, P_{fa} is equal to P_{fc}.

As a result, tas can be reformulated, using the above equations, as Eq.(2.15)

$$\begin{aligned} tas \;=\; & [(awh.E_d.P_{ep}) + (awh.E_r.P_{ep}) + (\frac{\frac{Q_d}{\eta_{ab}}.860}{LCV}.awh.P_{fc})] \\ & -[(W_{pgu}.C_{gc}.awh.P_{fc}) + (\frac{(Q_d + (\frac{(R_d-R_e)}{COP_{ac}}) - Q_c).awh.860}{LCV.\eta_{ab}}.P_{fc}) \\ & +((E_d - (W_{pgu}.\eta_{pgu}) + (\frac{(R_d - R_q)}{COP_{mc}}) + E_{ac}).awh.P_{ep}) \\ & +(awh.\delta_{smc})] \end{aligned} \tag{2.15}$$

In Eq.(2.15), due to the fact the efficiency of the cooling system is low, the heat generated by the CCHP system is more suitable to be used primarily by the heat demand of the plant. When it comes to the remaining heat not used by the heat demand, only the amount equal to the waste heat is used in AC if there is cooling demand. The remaining part of the cooling demand is met by MC.

The energy loads of the plant do not show a major volatility on an hourly and daily basis. Therefore, objective function is formulated on an annual basis rather than hourly and daily basis.

2.2 Investment Evaluation Criterias

The purpose of the objective function given in Eq.(2.15) is to maximize annual savings. Following the calculation of the total annual saving, the system has been evaluated in economical aspects with decision functions such as PP, DPP, NPV, B/C respectively given in Eqs. (2.16), (2.18),(2.19),(2.20)

$$PP = \frac{I_{cchp}}{tas} \tag{2.16}$$

One of the major disadvantages of simple payback period is its negligence for the time value of money. Instead, DPP in Eq.(2.18) accounts for the time value of money, as formulated in Eq. (2.17), by discounting the cash inflows provided by the investment.

$$P = A.\frac{(1+i)^n - 1}{(1+i)^n.i} \tag{2.17}$$

P represents the time value of money, corresponding the loan drawn from the bank. Therefore, in our case, P is equal to I_{chcp} . Under normal circumstances, A represents the monthly refunding amount that should be paid back to the bank. However, in our case, it corresponds to the compensation of monthly savings obtained from the investment. Thus, A corresponds to tas in USD divided by 12.

$$DPP = \frac{log\frac{(tas/12)}{((tas/12)-Icchp.i)}}{log(1+i)} \tag{2.18}$$

$$NPV = \Sigma\frac{B_n}{(1+i)^n} - \Sigma\frac{C_n}{(1+i)^n} \tag{2.19}$$

B_n and C_n are respectively the total benefits and costs of the systems within its economic life.

$$B/C = \Sigma\frac{B_n}{(1+i)^n}/\Sigma\frac{C_n}{(1+i)^n} \tag{2.20}$$

In the cases of when the value of the NPV turns out to be positive and the B/C is greater than 1, investments are considered acceptable and feasible.

Operational strategy is also an important factor to watch owing to its impact on the economic performance of CHP and CCHP systems. In this study, the CCHP system has been evaluated in the FEL condition as the plant in question has a non-fluctuating electricity demand both daily and seasonally. For the PGU, gas motor has been selected owing to its compatibility in the given demand capacity and load scheduling.

2.3 Methodologies

2.3.1 Methodology for CCHP Planning Under Uncertainty

In the first stage, the system has been evaluated as a sole CHP system in the light of the updated value of the variables in the section 3.1. In section 3.2, the system has been designed as a CCHP system by adding the AC with the intention of covering the cooling demand partly or fully. Setting the correct load capacity and scheduling

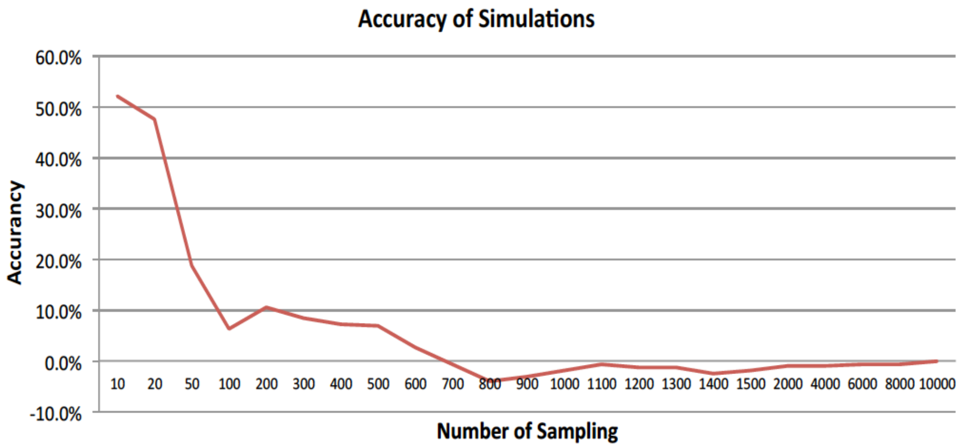

Figure 2.2 : Accuracy of Simulations.

is important while deciding on whether the most profitable system should be CHP or CCHP for a given plant. In the same section (3.2), Macro program in Microsoft Excel has been run in order to determine the most proper capacity for the absorption chiller that will maximize the *tas* After determining the most proper cooling load of the absorption chiller, the system has been re-evaluated in the economical aspect.

In the section 3.3, sensitivity analysis has been applied in the formula given in Eq.(2.21) with the purpose of seeing the impact of the variables on the result. Following this, a new formula has been created to analyze and calculate the effects of variables on the result of the objective function on a percentage basis.

$$IC = \frac{\theta(OP)}{\theta(IP)} = \frac{(change\ in\ output)}{(change\ in\ input)} \tag{2.21}$$

All the variables including economical and load parameters may change randomly within time. In this regard, the probability that the CCHP system can be more advantageous than the CHP system has been dug in the section 3.4 in consideration of the random changes of the load demand constrained by seasonality. In the section 3.5, GA is used to see the best case scenario in given constrains of uncertain variables. The result of this forms a reference for the comparison of the actual situation with the best case scenario.

As a last step, in the section 3.6, possible results of the *tas* have been re-calculated by using probabilistic models under stochastic method. All of the results obtained in these subsections are evaluated in the chapter 5.

The number of sampling in the probabilistic models is crucial to be able to reach the closest accuracy of the possible results. More number of sampling provides a more accurate result; however, it slows down the computing process and takes more computing time. Thereby, an error margin could be set to speed up the calculation.

As can be seen in Fig.2.2, 4.000 times sampling has provided an acceptable accuracy. Accordingly, this number of sampling was determined for computing of all the simulations in this study.

2.3.2 Methodology for Stochastic Evaluation of CCHP Systems

This study adopts stochastic modeling as a methodology, which forecasts by simulating future uncertainties. Theoretically, deterministic models do not consist of randomness but present one certain solution. Stochastic models, by contrast, contain uncertainties, randomness, and probabilities, serving to forecast in general. Stochastic modeling is a random search method with the following steps. First, the constraints of the variable are determined. If the variable has historical data, statistical features are identified. In light of these statistics, a suitable distribution is defined for the variable. Based on the assumption that the variable will act in accordance with a similar distribution in the future, random values for the variable are created and used in compliance with this distribution. Then, the best solution is chosen over a number of samples by analyzing the created random values and the changes in the objective function. While optimizations identify the best possible solution under the given constraints by maximizing desirable factors, modeling tries to represent or imitate reality in a given data set to predict future behavior.

Numerous studies have revealed how uncertainties affect energy plants. Ahmed and Elsholkami [50] presented a new methodology that combines energy planning under uncertainties of demand and fuel price with financial risk management. In their proposed methodology, a deterministic, mixed integer linear programming formulation was extended into a two-stage stochastic programming model to minimize cost subject to environmental constraints. Nowadays, many energy companies apply management techniques to cope with the risks that arise from uncertainties. Keskintas [51] investigated how market risk management could contribute in an energy company.

To simulate the existing uncertainties of power systems, several useful approaches have been introduced and developed, such as probabilistic models, robust optimization, and interval arithmetic [31]. It was concluded that the probabilistic model is most appropriate among these for assessing the impact of variations in electricity prices and load demand.

In uncertainty analysis and the stochastic method, the most important step is to determine which distribution should be used for which parameter. When determining the right distribution, not only the analysis of historical data but also the experience of experts in the energy field are crucial to forecasts. For instance, in [50], the parameters of load and fuel price were assumed to be discrete and finite probabilistic distributions. Since historical data concerning electricity prices and load demands are accessible for analysis in most instances, a probability density function (PDF) can be used to model these parameters. Trends in the future may not always reflect the distribution of the historical data. New influences in the future that are totally unknown may emerge, and how these new influences will affect parameters may also create uncertainty.

The methodology used in this study is summarized below. Visual Basic and MS Office applications were used for all modeling and to create random numbers based on the related PDF, as it is easy to implement the model in spreadsheets on a personal computer.

2.3.2.1 Parametric method

The parametric method is a technique that uses current data sets of variables to create a forecast. Two variables obtained from this data set are usually considered to be sufficient for a forecast to be made: mean (μ) and standard deviation (σ). The parametric method generally assumes that both variables act in accordance with random change that complies with the normal distribution, formulated in a variate (x) is formulated as in Eq. (2.22).

$$PDF(x,\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} exp(-\frac{(x-\mu)^2}{2\sigma^2}) \tag{2.22}$$

In other words, on the condition that the mean and standard deviation of a data set are available and act in compliance with the normal distribution, forecasting can be conducted by applying the parametric method to this data set. If a random variable (x) follows the normal distribution, it can be represented as in Eq. (2.23).

$$x \sim N(\mu, \sigma^2) \tag{2.23}$$

2.3.2.2 Monte Carlo method

The Monte Carlo method aims to assess the impact of uncertainty by taking historical data of related parameters into account. It approaches the solution to the problem by generating suitable random numbers for the variables based on the input probability distributions. Historical data that pertain to the related parameter are used as a guide to understand which parameters change based on which distribution function. A histogram is derived from the information obtained from this historical data, and the most approximate PDF is determined based on this histogram. Next, forecasting is conducted assuming that the parameter will again act in compliance with this set PDF. The methodology used in this method can be summarized as follows: (1) search maximum and minimum constraint values from the parameter's historical data of the parameter; (2) define categories and find the frequency of defined categories to generate a histogram of the parameter; (3) simulate the most suitable PDF from the generated histogram; and (4) create random numbers according to the simulated PDF.

2.3.2.3 Historical trend method

The historical trend simulation method requires no assumption regarding the statistical probability distributions of data. To help forecasting, it directly relies on past data. Assuming that a parameter's historical trend from previous years will follow the same trend in the future, forecasting is made by convergence with this trend. At this stage, better forecasting will be obtained by ensuring gradual convergence with the historical trend. In cases where historical data may not display an exact trend, it is acceptable to use a uniform distribution within some constraints. If the historical data set completely changes in compliance with the distribution function, better forecasting will be obtained by taking this distribution into account.

Trend analysis can be simply performed by regression. Linear regression, the most basic type of regression, is commonly used for predictive analysis. The line of best fit or prediction equation takes the form of Eq. (2.24).

$$Y = bX + a \tag{2.24}$$

The regression equation describes the relationship between the dependent or response variable (Y) and the independent or predictor variable (X). "b" is the slope of the regression, while "a" is the Y-intercept.

2.3.2.4 Scenario-based decision making method

Scenario-based decision-making is a technique that enables parameters to be categorized, helping estimate the possibility of occurrence for each category. These estimations use past experience with the system, historical data of the parameters, and/or the correlations among the parameters. In light of this analysis, the system is simulated based on each scenario and probable results are generated. By detecting within which limits the results are concentrated, probable results about the future can be estimated to occur within these limits.

Likewise, if x is an uncertain variable with a number of different parameters (i), the total number of scenarios (tns) is a function of the multiplying matrices of each scenario (M_{xi}), as in Eq. (2.25)

$$tns = \prod M_{xi} \quad (i = 1, 2, 3....) \tag{2.25}$$

If there are correlations among uncertain parameters, related parameters are evaluated together as a unique parameter.

The distributions used in this study are as follows: normal, BETA, triangular, PERT, and uniform. The choice of distribution is made based on the following factors: the method used (the normal distribution, for example, is used in the parametric method); the distribution with which the uncertain parameter acted in compliance in past years (as in the Monte Carlo method); and previous experiences, projections, or expectations. A triangular distribution is specified by its minimum, mean (most likely), and maximum values. It can be skewed to the left or right by the mean value. The PERT distribution is also specified by its minimum, mean (most likely), and maximum values; however, it constructs a smooth curve that places progressively more emphasis on values around (near) the most likely value. The BETA distribution is a continuous probability distribution with two parameters (α) and (β), which are named shape factors according to one of two rotational conventions. Finally, the uniform distribution is the simplest distribution for sampling a range of estimates. In the uniform distribution, every value, from the minimum to the maximum, is equally likely.

Related random numbers for the normal, BETA, triangular, PERT, and uniform distributions can be created in any random number generator, shown respectively as follows.

$NORM.INV.rand(); \mu; \sigma$

$BETA.INV rand()$; α; β

$TRIANGULAR.INV rand()$; min.(); most likely(); max()

$PERT.INV rand()$; min.(); most likely(); max()

$UNIFORM.randbetween(min; max)$

The system's uncertainties used in the aforementioned methods can be categorized as economic and technical. In [52], economic uncertainties in CCHP systems were defined as annual working hours, electricity prices, natural gas prices, and a discount rate, while technical uncertainties encompassed load uncertainties such as electricity, heating, and cooling loads as well as the efficiency of the power generation unit (PGU), efficiency of the mechanical and absorption chillers (MCs and ACs), and maintenance expenses of the whole system. The sensitivity analysis in the same study revealed that the most important variables that affect total annual savings are annual working hours, along with electricity and natural gas prices. In view of these results, this study treats as general uncertainties the variables of annual working hours, electricity prices, natural gas prices, and load demand for heating and cooling.

3. CCHP PLANNING UNDER UNCERTAINTY

The methodology explained in this study has been applied on a SME operating in the food industry located in Istanbul, Turkiye. The analysis is held based on the real operational, technical and economical data.

The proposed methodology helps decision makers choose the most proper system with the proper capacity and analyze whether the system is economically feasible or not or whether it will be feasible or not in near future when independent variables change randomly.

The energy demand pattern of the facility is like the following: Average electricity consumption (E_d) is around 1.000 kWh, which also includes the energy need of the mechanical cooling system. Average heat demand (Q_d) is around 500 kWh H in the form of warm water at 90 °C temperature produced by the boiler mainly to feed the dryer systems of the facility. The warm water is first sent to heat exchangers to warm the air and the warmed air is blown out to the product for drying process. The production of chilled water and the cooling storage form the cooling demand (R_d) of the facility.

As shown in Fig.3.1, heating demand is relatively stable within the day since the facility works 24 h non-stop. Not only daily demand, but also seasonality should be taken into account in the design stage of the system.

Seasonal load requirements are shown in Fig.3.2. As it can be seen in the figure, heating and cooling requirements in particular are fluctuating considerably in winter and summer seasons. This fluctuation impacts the capacity, design and the working conditions of the proposed system. Heating demand changes between 590 kWh H in winter time and 436 kWh H in summer time while cooling demand performs just in the opposite directions, changing between 285 kWh r in winter time and 620 kWh r in summer time.

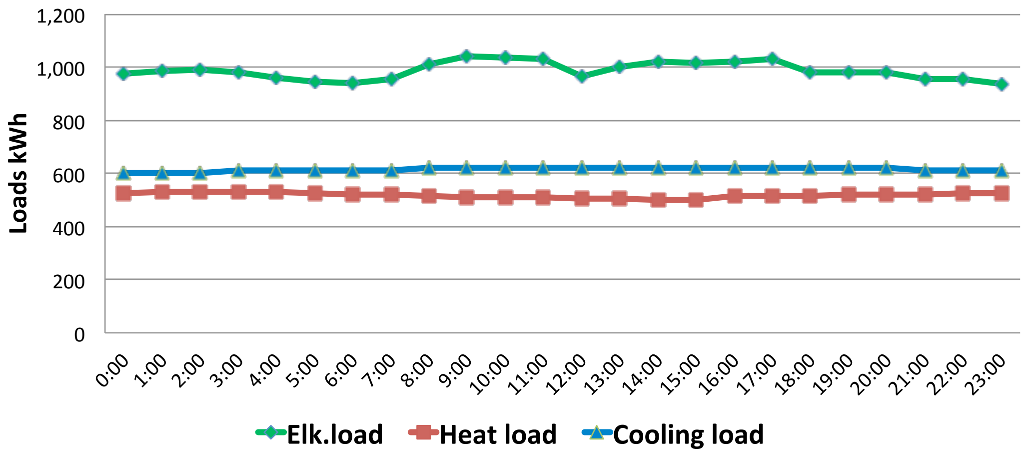

Figure 3.1 : Daily energy demands.

In addition to energy demands, other variables like grid electricity price (P_{ep}), natural gas price (P_{fc}), lower calorific value (LCV) of natural gas and exchange rate are indicated below.

$P_{ep} = 0.2050\ TL/kWhe$

$P_{fc} = 0.8460\ TL/m^3$

$LCV = 8{,}250\ kCal/m^3$

$XE_{\$/TL} = 2.2\ TL/USD$

Thus, objective faction, tas, is modified with currency as Eq.(3.1).

$$
\begin{aligned}
tas \;=\; & [[(awh.E_d.P_{ep}) + (awh.E_r.P_{ep}) + (\frac{\frac{Q_d}{\eta_{ab}}.860}{LCV}.awh.P_{fc})] \\
& -[(W_{pgu}.C_{gc}.awh.P_{fc}) + (\frac{(Q_d + (\frac{(R_d - R_e)}{COP_{ac}}) - Q_c).awh.860}{LCV.\eta_{ab}}.P_{fc}) \\
& +((E_d - (W_{pgu}.\eta_{pgu}) + (\frac{(R_d - R_q)}{COP_{mc}}) + E_{ac}).awh.P_{ep}) \\
& +(awh.\delta_{smc}.XE_{\$/TL})]]/XE_{\$/TL} \qquad (3.1)
\end{aligned}
$$

In the light of the input provided above, the annual energy cost of the facility has been calculated at 822,813 $USD/year$, on the condition that heating demand is met by AB at 95% thermal efficiency (η_{th}) and cooling demand is met by MC.

The most important part of the system design is to choose the correct PGU system. The system that complies best with the load ranges given in this study is the gas-motor-systems. Gas-motor-systems enable the heat energy production as much as the electricity energy produced by the system.

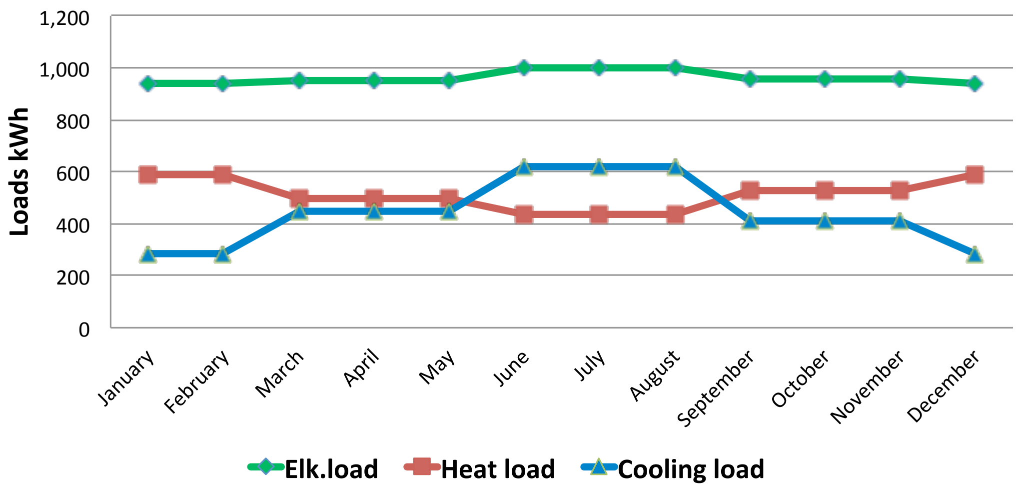

Figure 3.2 : Seasonally energy demands.

Table 3.1 : PGU technical data.

PGU type (Gas Motors)	PGU_{GM}
PGU electricity power (W_{pgu})	$800 kWhe$
PGU heating power (usable) (Q_c)	$912\ kWhH$
Electrify efficiency (η_e)	0.43
Thermal efficiency (η_{th})	0.49
Total efficiency (η_T)	0.91
Total PGU power (F_c)	1,880 kW
Specific gas consumption (C_{gc})	0.245 $Nm^3/kWhe$

The system becomes more advantageous economically when it works at full capacity. In such a situation, the lowest electricity load should be taken as a reference rather than the highest load in order for system to be able to work non-stop. This is an important criterion to consider particularly in cases of when the electricity surplus is not sold.

The technical features of the PGU system chosen based on the criteria mentioned above are shown in Table 3.1. Other technical and economic variables for the system design are indicated in Table 3.2.

3.1 Analysis Over The Case of a Sole CHP System

First and foremost, it is assumed that the entire cooling load required by the plant is met by the side of MC. In this case, the system works like a simple CHP system as in Fig.3.3, and it is analyzed in this way. Accordingly, the AC investment is not needed while the extra heat produced by the PGU system is not used actively.

Total annual saving then formulated as in Eq.(3.2)

Table 3.2 : System variables.

Variables	Values
Currency $(XE_{USD/TL})$	2,2
Annual working hours (awh)	7200 h
Electricity price (P_{ep})	0.205 TL/kWh
Natural Gas price (P_{fc})	0.846 TL/m^3
Electricity load (E_d)	1000 $kWhe$
Heating load (Q_d)	500 $kWhH$
Boiler efficiency(η_{boi})	0.95
HRS efficiency(η_{hrs})	0.97
Lower Calorific Value (LCV) of natural gas	8,250 $kCal/m^3$
Cooling load of plant (R_d)	620 $kWhr$
Mechanical cooling power (MC)	620 $kWhr$
Generated electricity by PGU (W_{pgu})	800 $kWhe$
PGU heat/power ratio Q_c/W_c	1.14
Heating power of PGU (Q_c)	912 $kWhH$
Investment cost of CHP (I_{chp})	450,000 $
Investment cost of CCHP (I_{cchp})	550,000 $
Specific maintenance cost per hour (δ_{smc})	9.72 $/h
Economic life of the system	12 years
Interest rate (i) annual	12

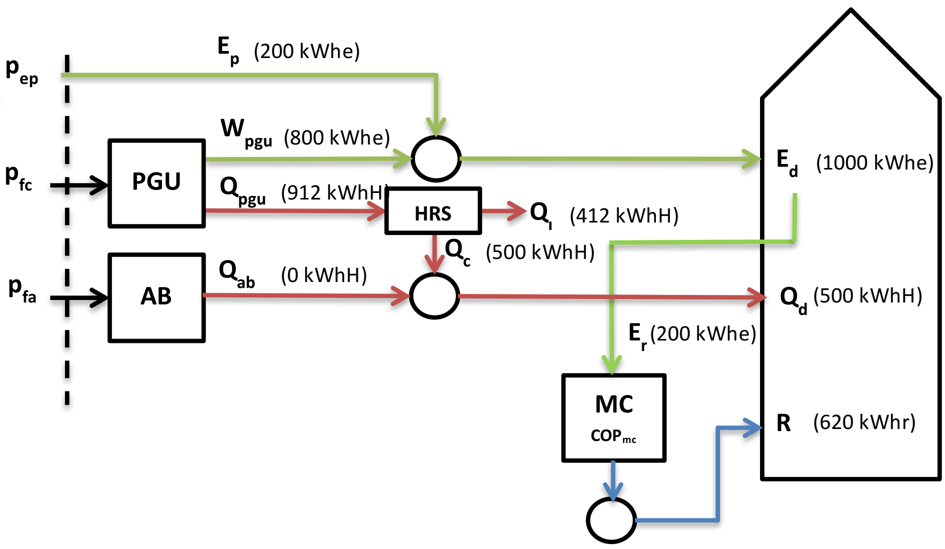

Figure 3.3 : CHP System.

Table 3.3 : Sole CHP system results.

System	tas	PP	DPP	NPV	B/C
GM_{chp}	85,961 $	5.23	8.29	N/A	0.65

Table 3.4 : COP of the chillers.

Chillers	Coefficient of performances
COP_{ac}	0.67
COP_{mc}	3.1

$$tas_{CHP} = OC_{SP} - OC_{CHP} \tag{3.2}$$

The economic analysis of the system under these circumstances is given in Table 3.3. In table, it can easily be concluded that a sole CHP system is not feasible investment for this plant.

3.2 Analysis Over The Case of a CCHP System

The CHP system is not a good selection particularly if there is unused heat in the system. Moreover, if the plant is in need of cooling, the selection of the CCHP system is considered inevitable. The CCHP system can be set by integrating AC into the CHP system as in Fig.2.1. Variables for the absorption cooling system are like the following: R_d, MC, R_q, Q_r, E_{ab} and I_{abs}. With a AC integrated into system, investment cost and maintenance cost became 550,000 USD and 70,000 USD respectively.

Primarily, when the absorption system has been designed in a way that it meets the entire cooling requirement of the plant as in Fig.3.4, the feasibility has turned out to be worse. The main reason why the system is not feasible in this way is because the efficiency of absorption chillers is very low compared to mechanical chillers as shown in Table 3.4. Hence, the heat to be used in the AC must be an extra heat on top of what the facility needs. In other words, if the facility needs heat, the heat the AC needs should not be met from the heat generated by PGU or AB. In both of these two cases, it is not possible for the system to be feasible. (Table 3.5)

Table 3.5 : CCHP with sole AC System results.

System	tas	PP	DPP	NPV	B/C
GM_{cchp}	N/A	N/A	N/A	N/A	N/A

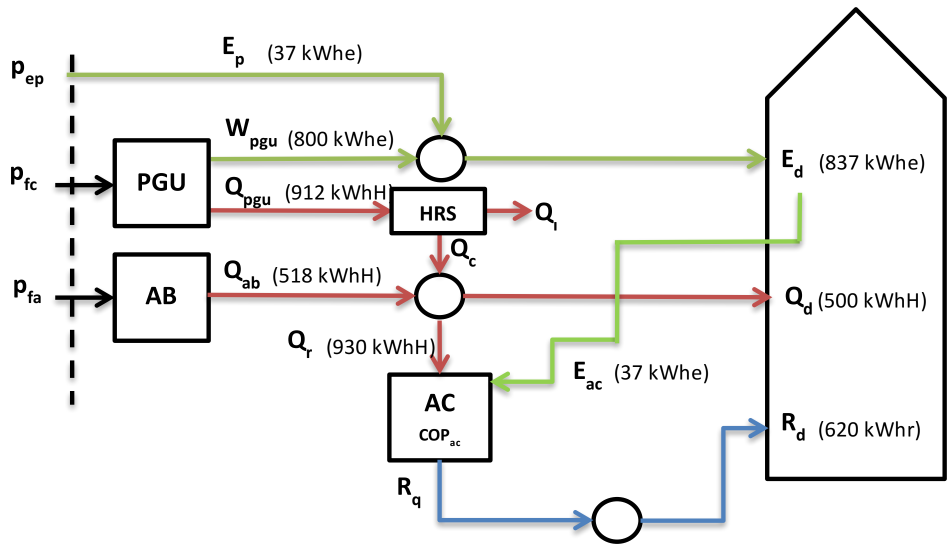

Figure 3.4 : CCHP with sole AC System.

The system must be re-evaluated to maximize the system profitability using the available heat source optimum. For this purpose, by the help of the Macro program in Microsoft Excel, the optimal point of the system has been detected by raising the load of the absorption system by 1%. The partial usage of the absorption system is called Coverage ratio (C_r) as it is indicated in Eq. (3.3).

$$C_r = \frac{R_q}{R_d} \tag{3.3}$$

If Q_r as in Eq. (3.4) modified with Eq. (2.13)

$$Q_r = R_q.COP_{ac} \tag{3.4}$$

then Q_r can be formulated as in Eq. (3.5).

$$Q_r = C_r.R_d.COP_{ac} \tag{3.5}$$

As seen in Fig.3.5, the optimum coverage ratio is found as 44%, which means that the 44% of the total cooling load will be met by the absorption system and the rest will be covered by MC. In another respect, the relationship between coverage ratio of absorption system and PP is shown as in Fig.3.6

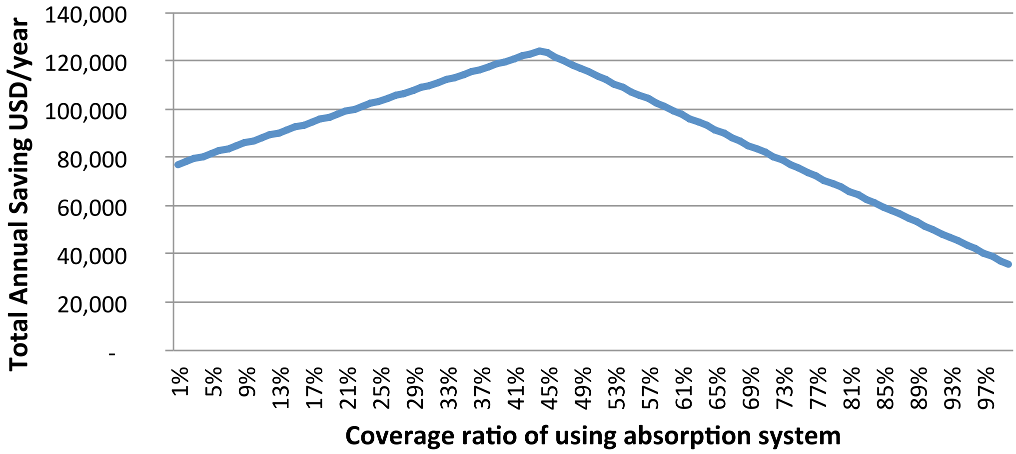

Figure 3.5 : Coverage Ratio and Total Annual Saving.

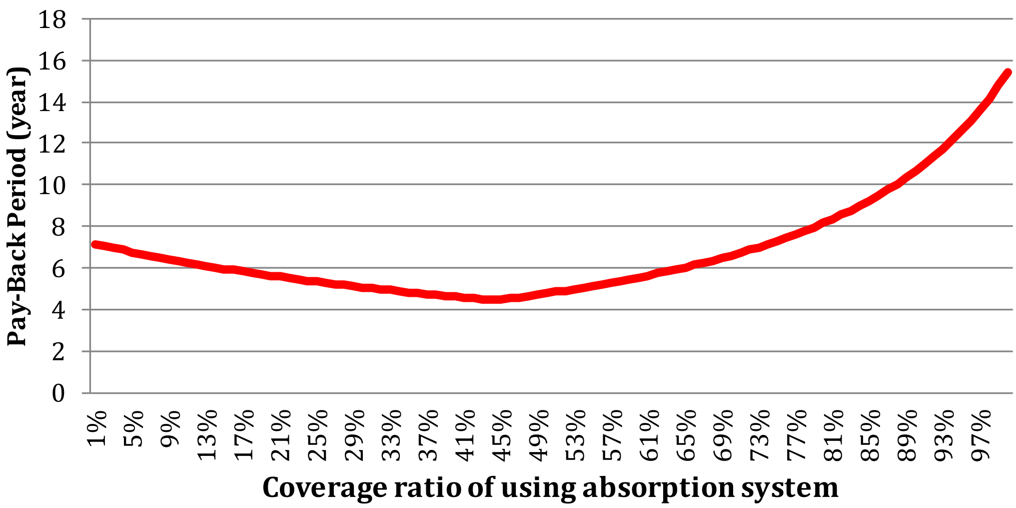

Figure 3.6 : Coverage Ratio and Pay-back Period.

Table 3.6 : Revised CCHP system results.

System	tas	PP	DPP	NPV	B/C
GM_{cchp}	124,020 $	4.15	5.78	N/A	0.82

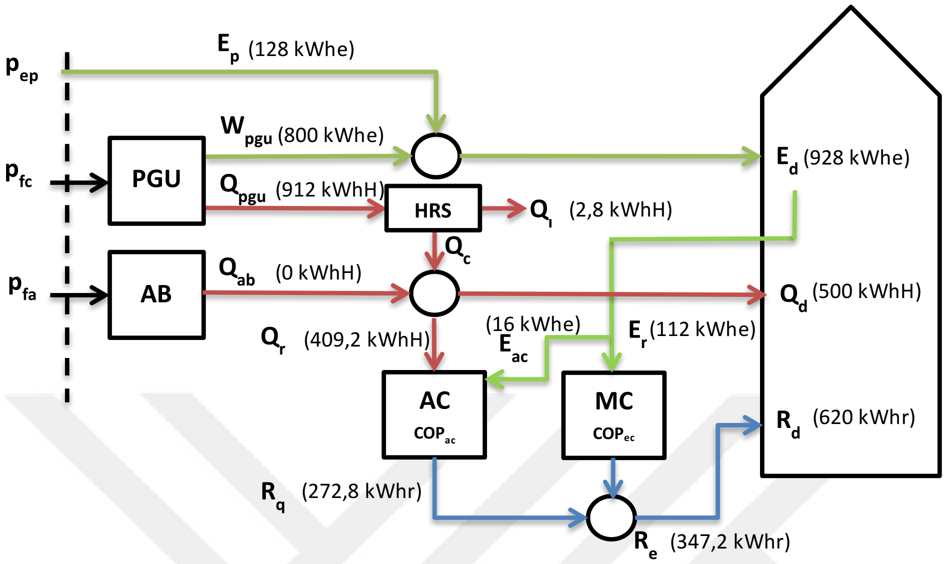

Figure 3.7 : CCHP with Optimum Load Distribution.

As a second step, the investment cost of the absorption system is revised based on the correct absorption cooling capacity. The revised absorption cooling system's investment cost is 65,000 USD. The results of the economic analysis made based on the new design are given in Table 3.6. Revised load distribution of the system based on the optimum coverage ratio is depicted as in Fig.3.7.

As an general concussion for CHP and CCHP systems;

if $Q_{pgu} > Q_d$ then CHP systems can be feasible.

Concerning CCHP systems, it should be Q_{pgu} - $Q_d > Q_r$ otherwise CCHP systems can not be feasible.

However if $Q_{pgu} < Q_d + Q_r$ then partial/optimum usage of MC and AC is needed.

In that case system must be designed as $Q_{pgu} > Q_d + C_r.R_d.COP_{ac}$

The feasibility of the CCHP system to be established based on the results of the technical and economical optimization is shown in the Table 3.6. In this situation, even though the system is not considered so advantageous, it is still considered investable.

However, the risks that may affect the profitability of the system stemming from the uncertainty of the variables within time should be taken into account.

3.3 Sensitivity Analysis of CCHP System

Within the scope of this thesis, the sensitivity analysis was applied to determine the degree of effect of each possible variable on the profitability of the system.

For sensitivity analysis, Eq.(2.21) is applied on the variables. In this case, inputs are like the following: currency, annual working hours, electricity price, natural gas price, thermal load, cooling load and annual maintenance cost. The output, in the meantime, is *tas*. All these inputs have linear correlation with the output. By using Microsoft Visual Basic, each input variable has been changed on a percent basis gradually while others were kept fixed.

$Subvariable()$

$Forratio = 1To100$

$\quad Cells(11,5).Value = initialvalue * (1 + ratio/100)$

$\quad Cells(ratio,10).Value = ratio$

$\quad Cells(ratio,11).Value = Cells(96,5).Value$

$\quad Cells(ratio,12).Value = Cells(98,5).Value$

$\quad Cells(ratio,13).Value = Cells(125,5).Value$

$\quad Cells(ratio,14).Value = Cells(105,5).Value$

$\quad Cells(ratio,15).Value = Cells(114,4).Value$

$Nextratio$

$EndSub$

The result between the inputs and the output has been formulated in Eq.(3.6), where all variables represent percentile changes.

$$\begin{aligned} tas \;=\; & (-1,59.XE_{\$/TL}) + (6,31.awh) + (5,13.P_{ep}) \\ & +(-3,52.P_{fc}) + (0,07.Q_d) + (-0,69.R_d) \\ & +(-0,61.amc) \end{aligned} \tag{3.6}$$

In each calculation, the fixed value of the result has been neglected. Thereby, an approximate correlation between the inputs and output is revealed on a percent basis. As can be seen in the formula, an increase in annual working hour, electricity price and annual maintenance cost have positive effect on the *tas*. That is to say, any increase in these parameters will also pave the way for an increase the annual saving. The fluctuation of heating and cooling load did not have a considerable influence on the result while currency and natural gas prices affect the result negatively. As a general example, if each input parameter in the formula increases by 5% in the following year, the annual saving approximately changes by 25.5%.

This formula also suggests which parameter is more influential in the feasibility study of the investment. Accordingly, the exchange rate is important in the investment phase particularly in the cases of when local energy costs and the cost of the machinery and components are priced in different currencies. In this study, energy costs are priced in the local currency TL while the main components of the CCHP system including power generation units or absorption systems are assumed to have been purchased in USD or EURO terms. As can be seen in Fig.3.8, the change of the local currency against the USD and/or Euro has a remarkable impact on the pay-back period of the investment. This figure clearly shows that exchange rate changes play a vital role in the viability of CCHP systems. The 45% change of the exchange rate in favor of the local currency doubles the payback period of the system. In addition, high interest rates in the country coupled with high exchange rates have a logarithmic effect on the amortization. Under these conditions, an increase larger than 25% in the exchange rates makes the investment completely meaningless.

Annual working hour, which is equal to the run time of the CCHP system per year, is one of the most critical parameters. For instance, if system works 10% less in a calculated year, which means 6.480 working hours instead of 7.200 hours, it reduces the annual saving by almost 60%. That is to say, it renders the investment worthless. In the case of a 10% increase in working hours, it has a favorable impact on the saving. The co-relation between annual working hours and the change of *tas*, PP and DPP is shown in Fig.3.9

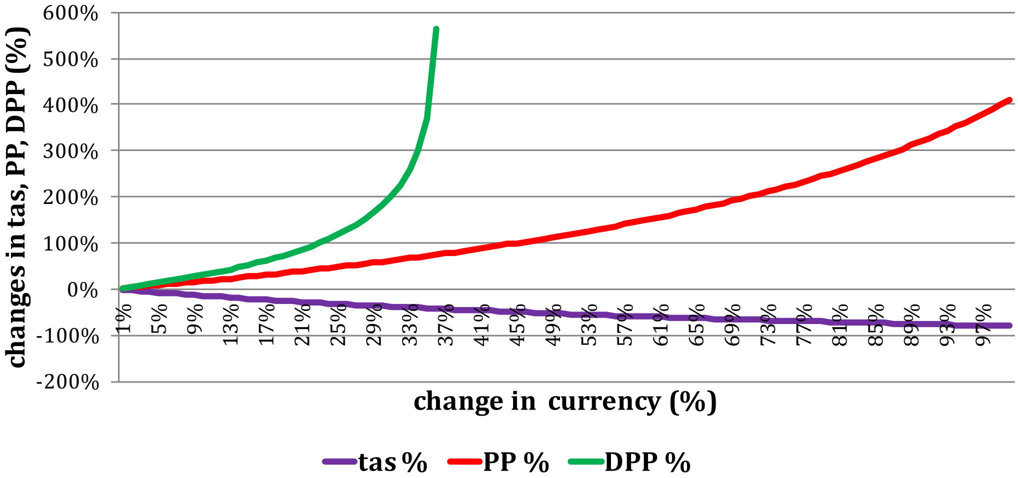

Figure 3.8 : The effect of currency on tas, PP, DPP.

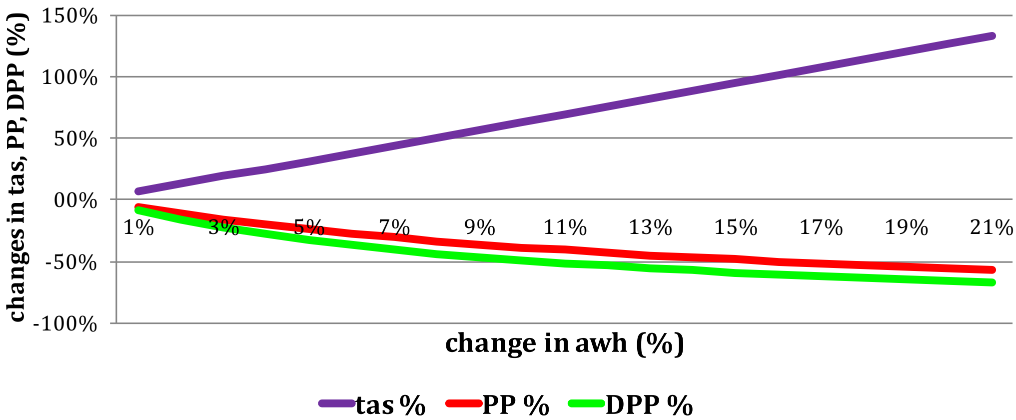

Figure 3.9 : The effect of annual working hour on tas, PP, DPP.

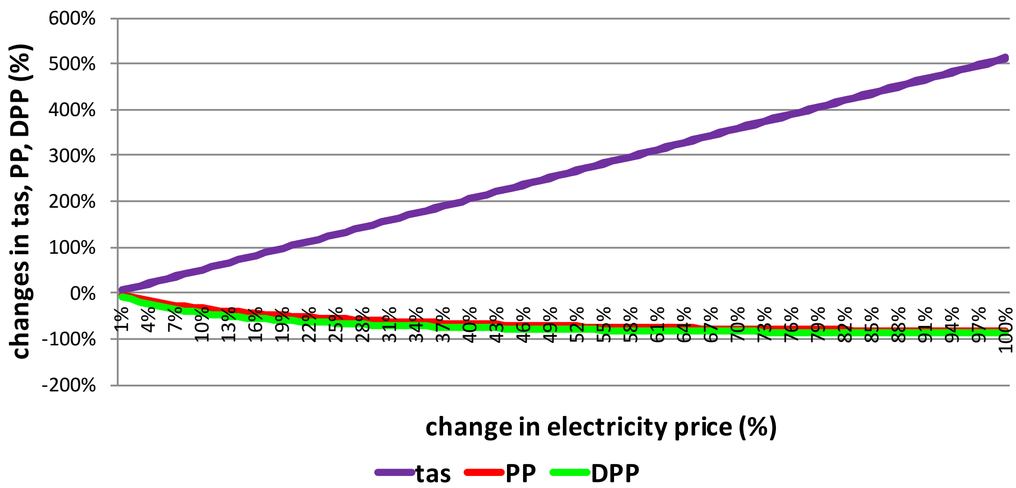

Figure 3.10 : The effect of electricity price on tas, PP, DPP.

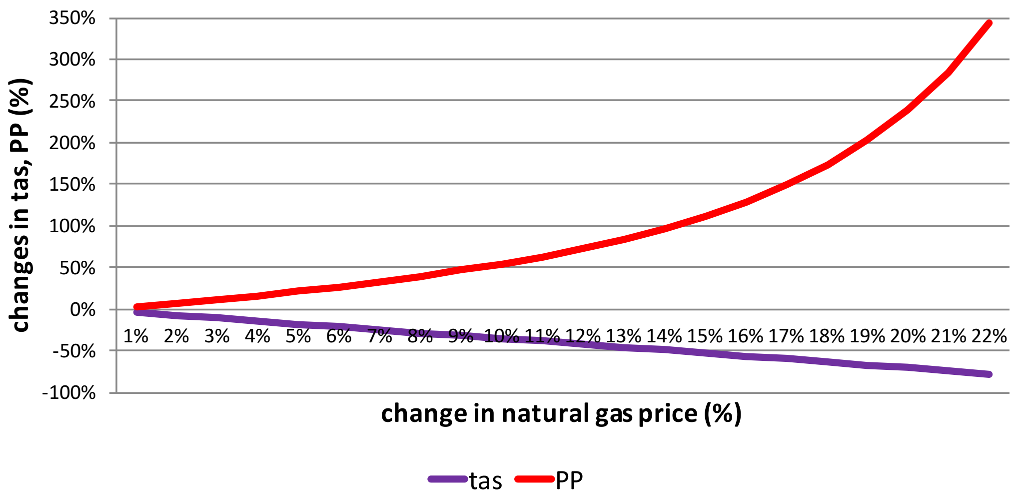

Figure 3.11 : The effect of natural gas price on tas, PP.

Moreover, electricity price is another important parameter. As long as electricity price is high or gains value against gasoline price, CCHP system becomes more profitable as it is seen in Fig.3.10

The increase in natural gas prices negatively affects the annual profit of the system as in Fig.3.11. In particular, an increase beyond 20% in natural gas prices results in a broken correlation between electricity and natural gas prices. This causes the annual savings to decrease more than 77% and PP to increase more than 300%, which consequently causes the system to lose its profitability.

The effects of heating, cooling loads and maintenance expenses on annual savings are as in Fig.3.12 . Although the increase in heating load does not affect the annual savings very seriously, the increase in cooling load and maintenance expenses has a negative effect on the system's annual profit, almost to the same degree.

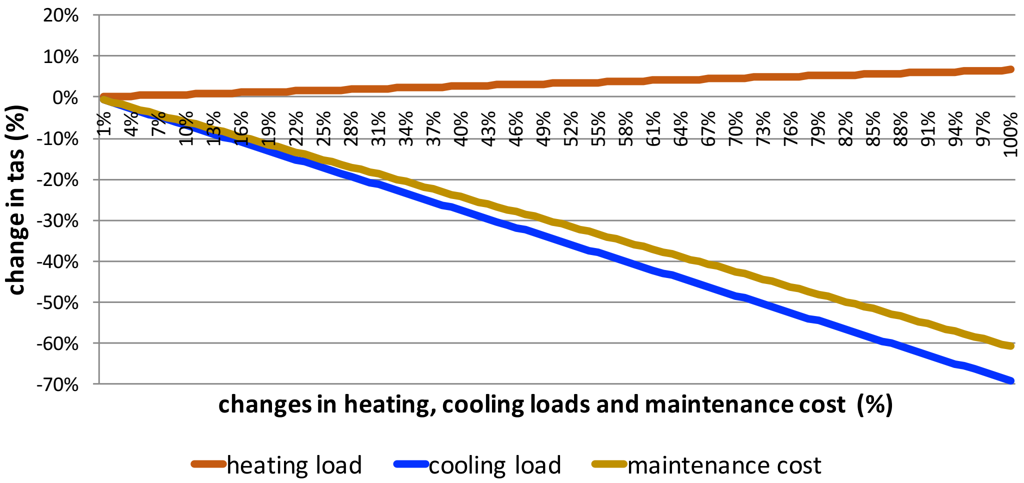

Figure 3.12 : The effect of heating, cooling loads and maintenance cost on tas.

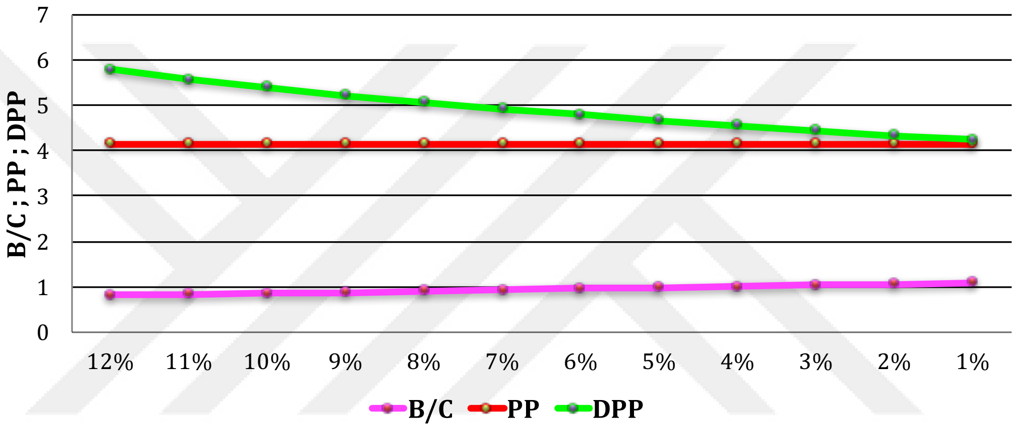

Figure 3.13 : The effect of discount rate on B/C, PP, DPP.

Discount rate is another important parameter to watch for investors as it shows the time value of money. Investors tend to finance their investments with bank loans. Therefore, rather than PP, DPP gives a clearer picture for the economic feasibility of the investment. Lower discount rate in the market means lower loan rate provided by the banks for the investment. In Fig.3.13, it is obvious that the higher the discount rate is, the longer the investment payback period takes, which is an undesired condition for decision makers. In this study, DPP has been calculated as almost 6 years while discount rate is assumed as 12%; however, DPP becomes equal to PP when the discount rate is at or close to zero, which encourages decision makers to undertake the investment.

Table 3.7 : Seasonal load constraints.

Variables	Constraints
Heating load (Q_d)	436 - 590
Cooling load of plant (R_d)	285 - 620
Coverage ratio (C_r)	0 - 100

B/C is another crucial indicator for decision makers. B/C should be bigger than 1 for the investable projects. According to the current economical parameters in Turkey, interest rate should be less than 7% to encourage CCHP investments.

3.4 Seasonal Effects of Loads and Determination of Best Fit Load Ranges

Since seasonal changes inevitably affect heating and cooling loads, seasonality is another crucial factor to watch in the evaluation phase of the investment. In this regard, running the system in different working modes in each season is considered more useful and profitable.

For this purpose, Eq.(3.1) has been modified by Eq.(3.3) and probable values (θ)

$$\begin{aligned}\theta_(tas)^{J:4,000} = {} & [[(awh.E_d.P_{ep}) + (awh.E_r.P_{ep}) + (\frac{\frac{Q_d}{\eta_{ab}}.860}{LCV}.awh.P_{fc})] \\ & -[(W_{pgu}.C_{gc}.awh.P_{fc}) + (\frac{(\theta(Q_d) + (\frac{(\theta(R_d)-R_e)}{COP_{ac}}) - Q_c).awh.860}{LCV.\eta_{ab}}.P_{fc}) \\ & +((E_d - (W_{pgu}.\eta_{pgu}) + (\frac{(\theta(R_d).(1-\theta(C_r)))}{COP_{mc}}) + E_{ac}).awh.P_{ep}) \\ & +(awh.\delta_{smc}.XE_{\$/TL})]]/XE_{\$/TL} \qquad (3.7)\end{aligned}$$

Eq.(3.7) has been simulated by changing the heating, cooling loads and absorption chiller's coverage rate randomly (J:4.000) within the ranges constrained by the seasonal maximum and minimum loads as in Table 3.7. The other variables have been assumed to have remained fixed in this simulation. The results revealed are summed up like the following:

- Possible maximum *tas* can be 140,688 USD

- Possible minimum *tas* can be 36,922 USD

- Possible average *tas* can be 101,141 USD

- With 40% possibility *tas* will be below 108,236 USD

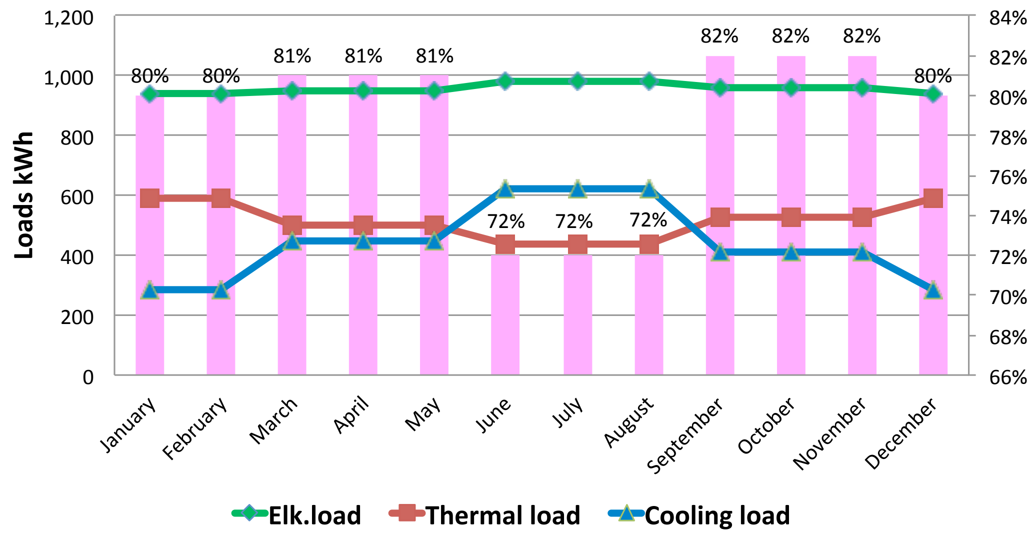

Figure 3.14 : The probability that CCHP system becomes advantageous.

- With 60% possibility *tas* will be below 84,867 USD

In this section, it is concluded that even seasonal changes of loads may result in an approximate gap of 100,000 USD between the possible maximum and minimum *tas*.

In Fig 3.14, an answer to the question of which form of system (CHP or CCHP) will be more profitable is sought based on the result of the simulations generated by the random changes of these three variables. The graph shows that the system will be profitable as CCHP throughout a year no matter what the load changes are.

At first glance, CCHP system is considered to be more profitable in summer time due to its requirements for more cooling load; however, as can be seen in Fig 3.14, the system bears the possibility of being less advantageous in summer time when compared to the winter time.

For the purpose of setting the most proper load schedule that will maximize the annual saving in CCHP system, a macro program in excel has been created as in below and the formula has been simulated by changing the heating and cooling load, and absorption chiller's coverage rate.

```
Subloadsim()
    Dimsatir
    satir = 3
        Fori = 200To1100Step100
            Cells(12,19) = i
            Cells(12,20) = i+100
                Forj = 200To650Step50
                    Cells(15,19) = j
                    Cells(15,20) = j+50
                        Fork = 0To9
                            Cells(17,19) = k/10
                            Cells(17,20) = (k+1)/10
                                Calculate
                                Cells(satir,43) = Cells(45,26)
                                Cells(satir,42) = (k+1)/10
                                Cells(satir,41) = k/10
                                Cells(satir,40) = j+50
                                Cells(satir,39) = j
                                Cells(satir,38) = i+100
                                Cells(satir,37) = i
                                satir = satir+1
                        Nextk
                Nextj
        Nexti
EndSub
```

In Fig.3.15 and Fig.3.16, all three parameters' changes are seen with the most proper load schedule being shown in dark red. The most proper loading schedules for this capacity are between 200-400 kWh in heating load, between 450-600 kWh in cooling load and between 25%-50% coverage rate of using absorption system.

3.5 Best Case Scenario by Using GA

Determining the best and worst case scenarios in given constraints enables decision makers to see how much the result of the analysis approach the best and/or the worst limits. Recognizing these limits in the investment is essential in order to evaluate the possible advantages and risks that may come up in the short and/or long term in line with the changes of the variables within time.

The Genetic Algorithm method has been selected as a part of the optimization theories in order to determine the best case scenario by using Microsoft Excel Solver. Algorithm has been run with all the constraints indicated in Table 3.8. Exchange rate, annual working hours, electricity price and natural gas price have been constrained

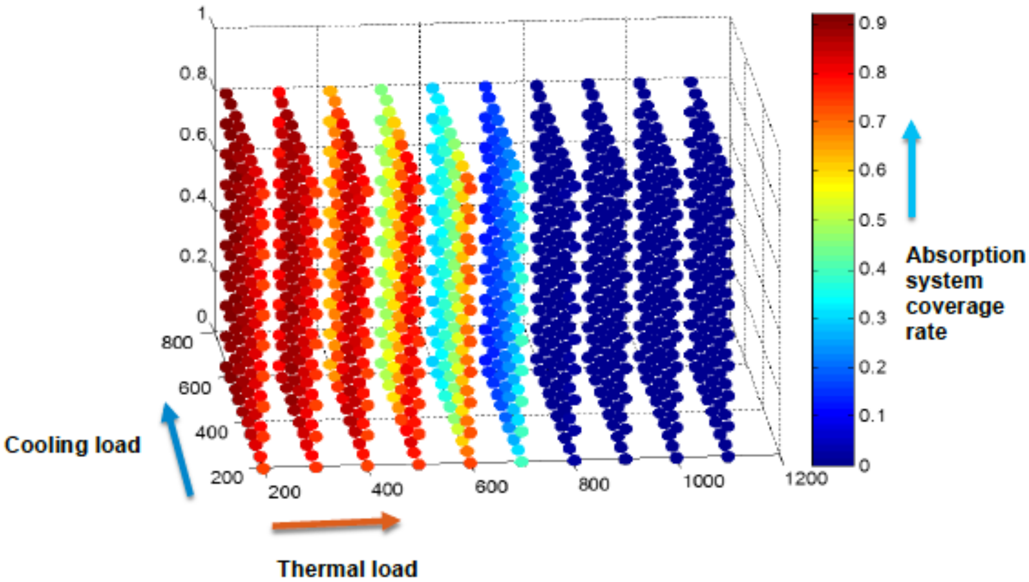

Figure 3.15 : The best fit load ranges.

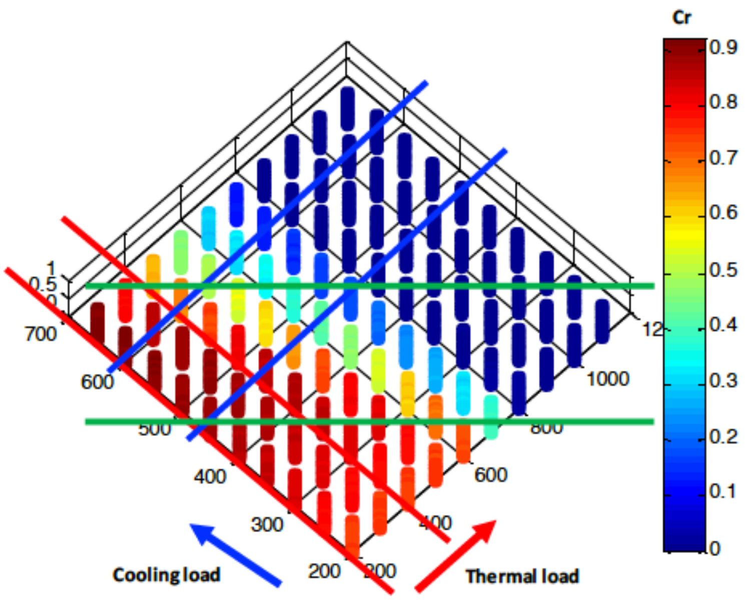

Figure 3.16 : The best fit load ranges (plan view).

Table 3.8 : Constraints of variables.

Variables	Constraints
Currency $(XE_{USD/TL})$	1.87 - 2.53
Annual working hours (awh)	6,120 - 8,250
Electricity price (P_{ep})	0.174 - 0.235
Natural Gas price (P_{fc})	0.719 - 0.973
Heating load (Q_d)	436 - 590
Cooling load of plant (R_d)	285 - 620
Coverage ratio (C_r)	0 - 100
Investment cost of CHP (I_{chp})	430,000 - 450,000
Investment cost of AC (I_{abs})	64,000 - 65,000
Maintains cost of the system (amc)	58,000 - 70,000

Table 3.9 : Best case scenario.

System	tas	PP	DPP	NPV	B/C
$GM_{cchp,GA,}$	426,579 $	1.19	1.29	1,785,578 $	3.06

+/- 15% of their current values. Loads and coverage ratio have been constrained by seasonal effects as indicated above.

PP and DPP are strongly affected by investment cost. Any possible discount in the process of the procurement of PGU and absorption system makes the investment more attractive in terms of decision making. Thereby, an approximate discount of up to 5% in machinery part is assumed to have been obtained after negotiation with machinery providers.

Under these limitations, the economic analysis of the investment reveals that the best case scenario mentioned above seems very promising to undertake this investment as shown in Table 3.9. However, the probability of occurrence of the best case scenario is important, which has been studied in the next section.

3.6 Non-parametric Stochastic Method

In this section, the probability of the occurrence of total annual saving has been investigated under the stochastic method, where it is assumed that all the variables have changed as uniformly within a +/- 15% range in currency, annual working hour, electricity price and natural gas price without complying with any distribution function. Apart from these variables, seasonal heating and cooling loads, and coverage ratio have changed randomly in a respective order of the following: Q_d: 436-590 kWh,

R_d: 285-620 kWh and C_r: 0%-100% as in Table 3.8. In this method, the correlation among the variables, their historical trends and probability density functions have been disregarded.

The model has been simulated by 4,000 times under these circumstances, the results of which are shown like below;

- Possible maximum *tas* can be 376,953 USD/year

- Possible minimum *tas* can be -204,800 USD/year, which means the investment is at a loss.

- Possible average *tas* can be 93,736 USD/year, which is the most probable result.

Following the analysis made above on the probability of occurrence for CCHP system, below seeks an answer to the question of whether CHP or CCHP system is more profitable.

If CHP system is established under the conditions mentioned above,

- With 40% probability, *tas* can be above 112,943 USD/year

- With 60% probability, *tas* can be above 64,100 USD/year

If CCHP system is established under the conditions mentioned above,

- With 40% probability, t*as* can be above 109,610 USD/year

- With 60% probability, *tas* can be above 64,347 USD/year

As it is indicated in section 3.4, the green lines in figure show the possible occurrence limits in case of just thermal loads changes.

The confidence level, which is a criterion to take the decision for the investment, is assumed to be 100,000 USD for tas and 4.5 year as pay-back period. As can be seen in Fig.3.17, the possibility that the investment is above the confidence level, that is to say the investment is feasible, corresponds to 35%. In other words, the investment may not be feasible with 65% of possibility. Nevertheless, one should bear in mind that there is no time limitation in this simulation. As it is not clear when these possibilities may

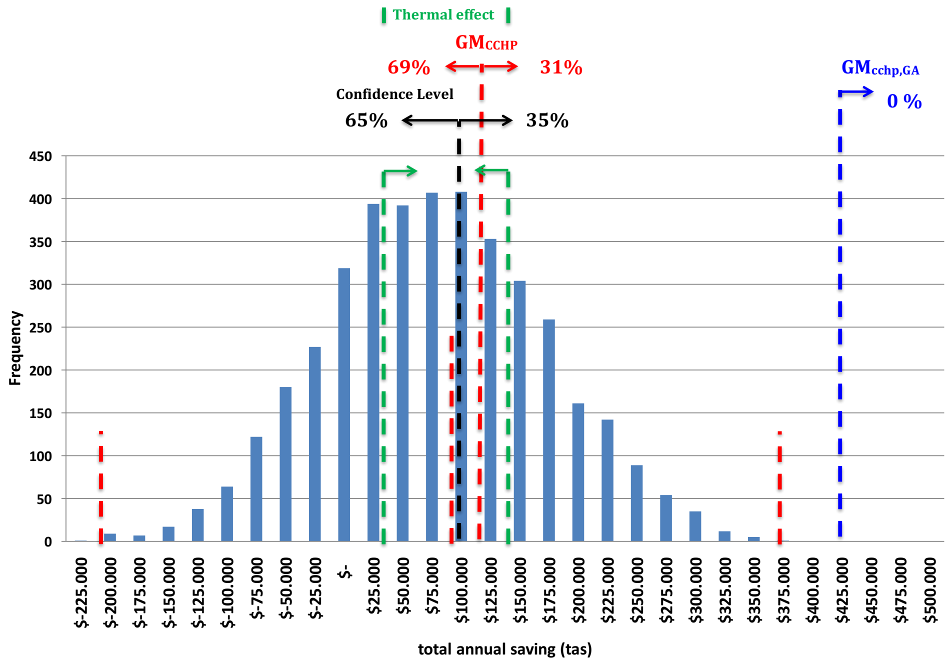

Figure 3.17 : Distribution function of tas.

occur, it suggests that they may take place any time during the economic life of the investment.

4. STOCHASTIC EVALUATION OF CCHP SYSTEMS

The first stage of the thesis presented a very wide range of possibilities to assess the profitability of the system.

At this stage, as in [53], a re-evaluation was carried out in order to make a clearer analysis considering the historical data of the independent variables that affect the applicability of the system and the correlations between the variables, if any, and the probability density functions of the variables as

In addition, the change between the local currency and foreign currencies has been neglected in order to put forward a more global point of view. Therefore, electricity and natural gas prices are referred in dollars.

On account of the current inputs provided above, the total annual savings of the facility from the installation of the CCHP system has been calculated at \$187,284 per year, in accordance with P_{ep} = 0.0899 $USD/kWhe$ and P_{fc} = 0.2895 USD/m^3.

The payback period in Eq.(2.16) is the simplest way for investors to evaluate the feasibility of the investment. The PP is calculated as 2.93 years with the current values of the variables.

In Eq.(2.15), among the parameters that constitute tas, there are five main parameters that directly and strongly affect tas. These are respectively as follows: P_{ep}, P_{fc}, awh, Q_d, and R_d; the constraints that belong to these parameters are shown in Table 4.1.

The uncertain parameters mentioned above have probable values(θ) for each methods. The tas, which will be constituted by the results of these values, is formulated as in Eq.(4.1).

Table 4.1 : Constraints of uncertain variables.

Variables	Constraints
Annual working hours (awh)	6,120 - 8,250
Electricity price (P_{ep})	0.077 - 0.123
Natural Gas price (P_{fc})	0.264 - 0.533
Heating load (Q_d)	436 - 590
Cooling load of plant (R_d)	285 - 620

$$
\begin{aligned}
\theta_(tas)^{J:1,000}_{method} = \ & [(\theta(awh).E_d.\theta(P_{ep})) + (\theta(awh).E_r.\theta(P_{ep})) \\
& + (\frac{\frac{\theta(Q_d)}{\eta_{ab}}.860}{LCV}.\theta(awh).\theta(P_{fc}))] - [(W_{pgu}.C_{gc}.\theta(awh).\theta(P_{fc})) \\
& + (\frac{(\theta(Q_d) + (\frac{(\theta(R_d) - R_e)}{COP_{ac}}) - Q_c).\theta(awh).860}{LCV.\eta_{ab}}.\theta(P_{fc})) \\
& + ((E_d - (W_{pgu}.\eta_{pgu}) + (\frac{(\theta(R_d) - R_q)}{COP_{mc}}) + E_{ac}).\theta(awh).\theta(P_{ep})) \\
& + (\theta(awh).\delta_{smc})]
\end{aligned}
\tag{4.1}
$$

The value of *tas*, which consists of uncertainties about the future, is studied in four different methods and the overall PDF of probable *tas* values was created after 1,000 simulations(*J*) for each method.

Used as data-sets are electricity and natural gas prices from the past 11 years (Table 4.2), heating and cooling monthly demand of last 10 years, and the annual working hours of last 20 years. All estimations are provided based on these historical data.

4.1 Parametric Method

In this method, uncertain parameters, including energy prices, load demand, and the running time of the CCHP system, are assumed to follow a normal PDF. Eq.(4.2) represents the PDF for a normal distribution, where the coefficients (μ) and (σ) are equal to the mean and standard deviation of the corresponding uncertain parameters, respectively.

$$
PDF(x) = \frac{1}{\sigma\sqrt{2\pi}} exp(-\frac{(x-\mu)^2}{2\sigma^2}) \quad (x = P_{ep}, P_{fc}, Q_d, R_d, awh) \tag{4.2}
$$

Table 4.2 : Historical data of electricity and natural gas prices.

Years	Quarters	P_{ep}	Change	P_{fc}	Change
n	Q's	($\$/kWhe$)	(%)	($\$/m^3$)	(%)
2005	July - September	0.0778	0.00	0.2583	0.00
2005	October - December	0.0770	-1.01	0.2703	4.62
2006	January - March	0.0784	1.80	0.2909	7.64
2006	April - June	0.0720	-8.23	0.2805	-3.59
2006	July - September	0.0707	-1.79	0.2917	3.99
2006	October - December	0.0736	4.14	0.3171	8.73
2007	January - March	0.0812	10.35	0.3270	3.12
2007	April - June	0.0859	5.71	0.3450	5.50
2007	July - September	0.0896	4.38	0.3588	3.99
2007	October - December	0.0970	8.27	0.3872	7.91
2008	January - March	0.1190	22.60	0.4099	5.85
2008	April - June	0.1159	-2.56	0.4318	5.35
2008	July - September	0.1219	5.11	0.5330	23.44
2008	October - December	0.0965	-20.77	0.5313	-0.31
2009	January - March	0.1054	9.19	0.4099	-22.86
2009	April - June	0.1120	6.21	0.3284	-19.87
2009	July - September	0.1167	4.21	0.3437	4.65
2009	October - December	0.1176	0.77	0.3456	0.55
2010	January - March	0.1215	3.36	0.3420	-1.05
2010	April - June	0.1192	-1.91	0.3354	-1.92
2010	July - September	0.1216	1.98	0.3415	1.82
2010	October - December	0.1273	4.68	0.3533	3.46
2011	January - March	0.1169	-8.15	0.3285	-7.02
2011	April - June	0.1177	0.68	0.3313	0.86
2011	July - September	0.1062	-9.77	0.2990	-9.77
2011	October - December	0.1094	3.03	0.3214	7.51
2012	January - March	0.1120	2.41	0.3295	2.50
2012	April - June	0.1210	7.99	0.3875	17.62
2012	July - September	0.1212	0.20	0.3881	0.16
2012	October - December	0.1268	4.57	0.4280	10.27
2013	January - March	0.1273	0.43	0.4300	0.47
2013	April - June	0.1235	-3.03	0.4171	-3.01
2013	July - September	0.1154	-6.52	0.3903	-6.41
2013	October - December	0.1123	-2.75	0.3799	-2.69
2014	January - March	0.1027	-8.52	0.3481	-8.36
2014	April - June	0.1082	5.33	0.3653	4.94
2014	July - September	0.1055	-2.41	0.3565	-2.40
2014	October - December	0.1099	4.16	0.3701	3.80
2015	January - March	0.1009	-8.24	0.3394	-8.28
2015	April - June	0.0933	-7.53	0.3143	-7.41
2015	July - September	0.0907	-2.76	0.3057	-2.72
2015	October - December	0.0881	-2.84	0.2973	-2.76
2016	January - March	0.0907	2.86	0.2920	-1.79
2016	April - June	0.0891	-1.71	0.2871	-1.68

Table 4.3 : Statistics data of electricity and natural gas prices.

Symbol	Definition	P_{ep}	P_{fc}
μ	Average	0.1042	0.3532
σ^2	Variance	0.00028	0.00344
σ	Standard Deviation	0.0168	0.05866
$\alpha 3$	Skewness	-0.5121	1.1891
$\alpha 4$	Kurtosis	-0.9845	2.0659

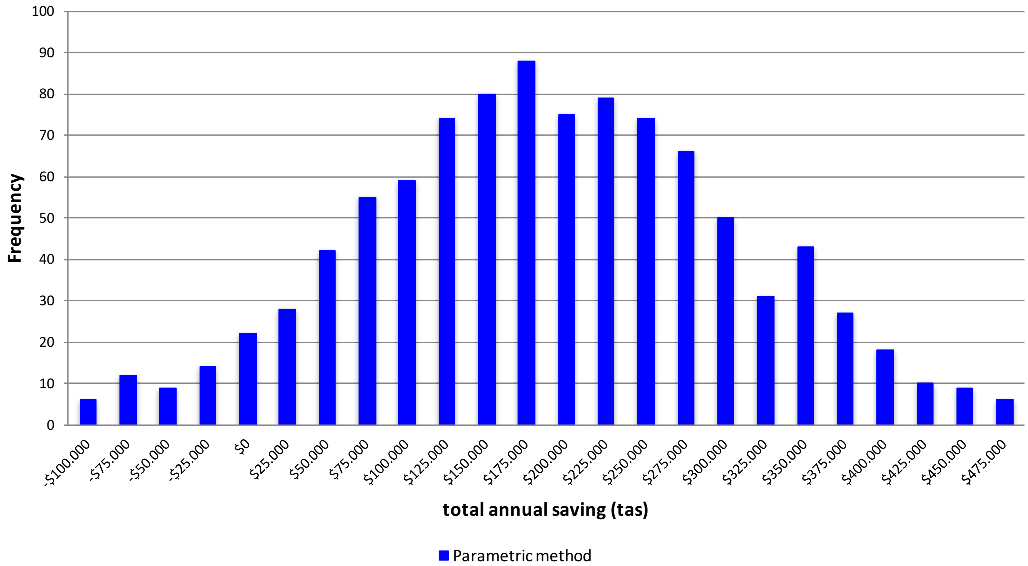

Figure 4.1 : The PDF of *tas* for Parametric Method.

Based on the parametric method, the probabilistic values of each uncertain parameter are assumed as follows. The mean and standard deviation of these parameters (Table 4.3) are based upon data from the past 11 years.

$$\theta_{PM}(awh) = NORM.INV\,rand();\ \mu(7{,}200);\ \sigma(700)$$

$$\theta_{PM}(P_{ep}) = NORM.INV\,rand();\ \mu(0.1042);\ \sigma(0.0168)$$

$$\theta_{PM}(P_{fc}) = NORM.INV\,rand();\ \mu(0.3532);\ \sigma(0.05866)$$

$$\theta_{PM}(Q_d) = NORM.INV\,rand();\ \mu(500);\ \sigma(50)$$

$$\theta_{PM}(R_d) = NORM.INV\,rand();\ \mu(450);\ \sigma(150)$$

The random numbers created in accordance with the normal distribution are evaluated in Eq.(4.1), and the overall composed distribution for Parametric method, $PDF(tas)_{PM}$, after 1,000 simulations is shown in Fig.4.1 and Fig.4.11

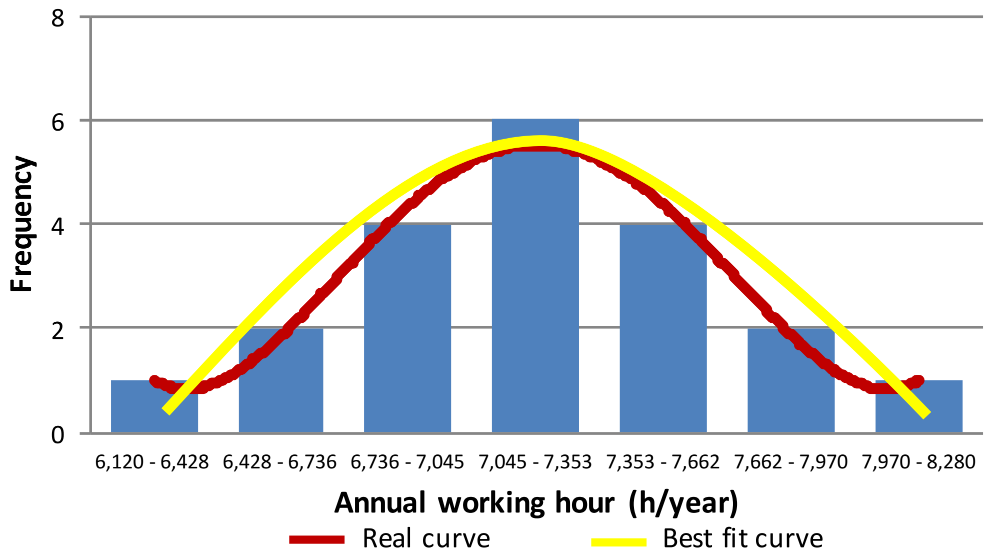

Figure 4.2 : The histogram of annual working hours of the plant.

4.2 Monte Carlo Method

In this method, the uncertain parameters are assumed to act in the future in compliance with the probability distribution of the past years. The annual working hours of the plant varied from 6,120 hours to 8,280 hours depending on the economic situation of the country, the volume of orders taken and unpredictable technical outages. Considering the performance on these values over the last 20 years, *awh* is estimated to be mainly closer to "the most likely value", which is 7,200 hours for this plant as in Fig.4.2. Therefore, the most appropriate distribution for *awh* is defined to be PERT distribution.

For P_{ep} and P_{fc}, the prices from each quarter over the past ten years were analyzed. In view of this analysis, the histograms generated for P_{ep} and P_{fc} are depicted in Fig.4.3 and in Fig.4.4. The most proper distribution is found based on the histogram by specifying suitable shape factors. As can be concluded from the graphs, electricity and natural gas prices have mostly acted in compliance with the BETA distribution as in Fig.4.3 and in Fig.4.4.

When analyzing monthly data from the past 10 years, as shown in Fig.4.5, the plant's heating demand and cooling demand have respectively acted in compliance with normal distribution and triangle distribution within these years.

Thus, the probable values of each parameter for the Monte Carlo simulation are defined as follows:

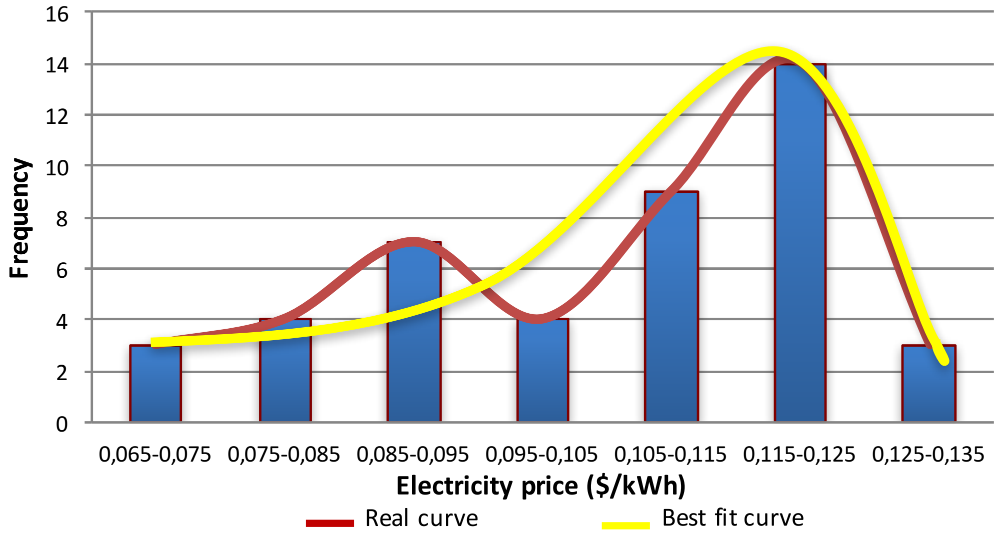

Figure 4.3 : The histogram of electricity price.

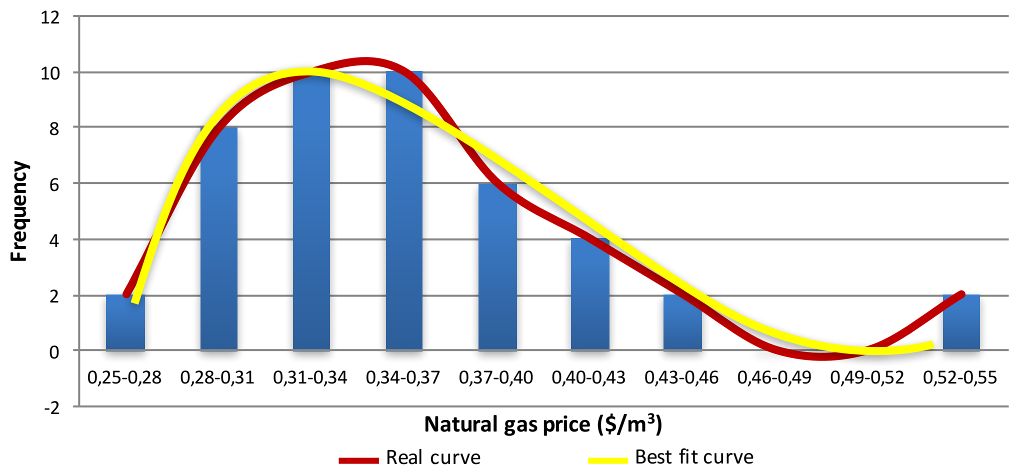

Figure 4.4 : The histogram of natural gas price.

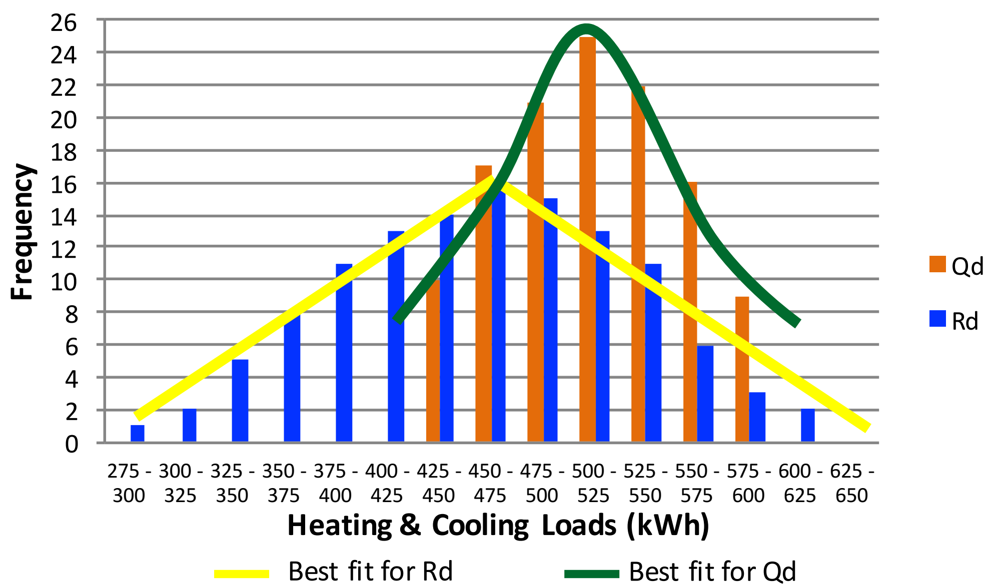

Figure 4.5 : The histogram of heating & cooling loads.

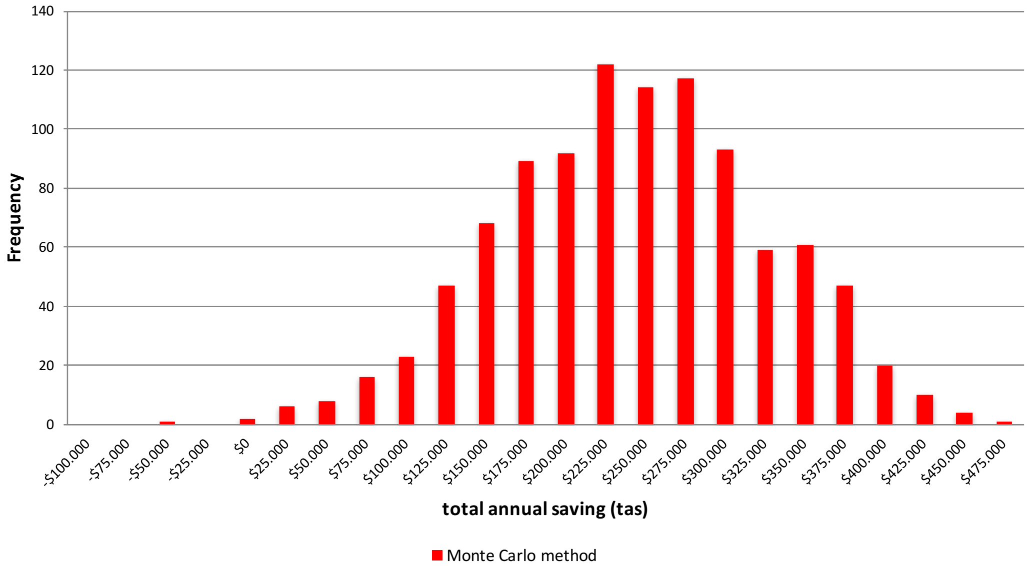

Figure 4.6 : The PDF of *tas* for Monte Carlo Method.

$\theta_{MCM}(awh) = PERT.INV rand()$; min.(6,120); most likely(7,200); max(8,280)

$\theta_{MCM}(P_{ep}) = BETA.INV rand()$; α (3.5,1.8); β (0.077,0.1273)

$\theta_{MCM}(P_{fc}) = BETA.INV rand()$; α(1.5,3.4); β(0.2583,0.5330)

$\theta_{MCM}(Q_d) = NORM.INV rand()$; μ(500); σ(50)

$\theta_{MCM}(R_d) = TRIANGULAR.INV rand()$; min.(285); most likely(450); max(620)

The random numbers created in accordance with the defined distributions are evaluated in Eq.(4.1), and the overall distribution of the Monte Carlo method, $PDF(tas)_{MCM}$, over 1,000 simulations is also shown in Fig.4.6 and Fig.4.11

4.3 Historical Trend Method

The capacity expansion of the studied plant is not planned for the coming years. Accordingly, heating and cooling loads are anticipated to remain within the defined constraints. Regarding *awh*, it is similarly not anticipated to exceed the constraints of 6,120 - 8,280 hours. Because of these constraints, the PDFs formed by the historical data of these three parameters can be used. As with the Monte Carlo method, the *awh*, Q_d and R_d parameters are assumed to respectively follow the PERT, normal, and triangular distributions.

However, P_{ep} and P_{fc} prices can move in any trend as they are linked to many independent parameters. Therefore, in this method, the historical trends of past data

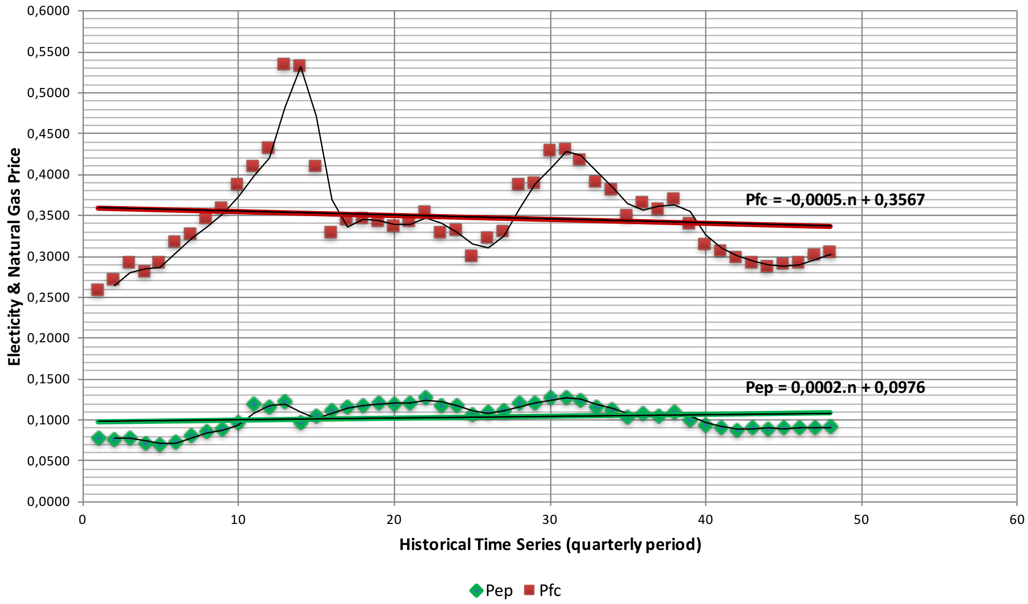

Figure 4.7 : Historical time series of Pep & Pfc.

are considered for P_{ep} and P_{fc}, with trend analysis performed by a simple regression method as in Fig.4.7. For electricity and natural gas prices, Eq.(2.24) is adapted as in Eqs.(4.3) and Eq.(4.4).

Accordingly, P_{ep} and P_{fc} are assumed to act in compliance with their historical trend, calculated by multiplying the slope of regression (b) by the past years (divided into quarters) and adding the regression constant (a).

$$P_{ep} = b_{ep}.n + a_{ep} \tag{4.3}$$

$$P_{fc} = b_{fc}.n + a_{fc} \tag{4.4}$$

Thus, P_{ep} and P_{fc} are formulated as:

$P_{ep} = 0.0002.n + 0.0976$ and $P_{fc} = -0.0005.n + 0.3567$

Regarding the other parameters, awh has time constraints and Q_d and R_d have load constraints, so they cannot be subject to trend analysis. Accordingly, they are assumed to act as estimated in the previous method.

The probable values of each parameter based on the historical trend method are defined as follows.

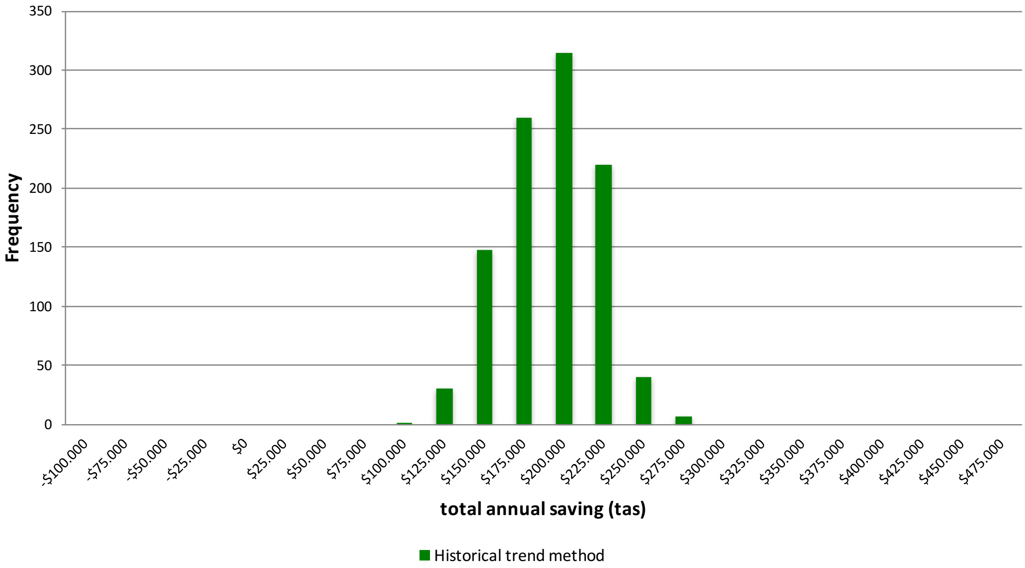

Figure 4.8 : The PDF of tas for Historical Trend Method.

$\theta_{HTM}(awh) = PERT.INV\,rand()$; min.(6,120); most likely(7,200); max(8,280)

$\theta_{HTM}(P_{ep}) = b_{ep}.UNIFORM.randbetween(0;48) + a_{ep}$

$\theta_{HTM}(P_{fc}) = b_{fc}.UNIFORM.randbetween(0;48) + a_{fc}$

$\theta_{HTM}(Q_d) = NORM.INV\,rand()$; $\mu(500)$; $\sigma(50)$

$\theta_{HTM}(R_d) = TRIANGULAR.INV\,rand()$; min.(285); most likely(450); max(620)

In the simulation, P_{ep} and P_{fc} are defined by multiplying the slope of regression by the uniform random numbers created between 0 to 48 which correspond quarterly prices belonging to the past years and then adding the regression constant.

The result of the analysis shows that the slope of prices is relatively horizontal and therefore, the simulation is made within the constraints of the historical data.

If the slope turned out to be relatively more vertical either in the positive or negative direction, the constraints would be determined by encompassing the possible data in the future.

Possible value of tas are calculated using Eq.(4.1) and the random numbers created in accordance with the above defined distributions.

The overall distribution of tas, $PDF(tas)_{HTM}$, is simulated as in Fig.4.8 and Fig.4.11

Table 4.4 : Scenarios for run-time of the CCHP system.

Scenarios	pessimistic	likely	optimistic
awh	4,980-6,240	6,240-7,500	7,500-8,760
PDF	Norm.Dist.	Norm.Dist.	Norm.Dist.
μ	5,610	6,870	8,130
σ	630	630	630
$\theta(scenario)$	$Norm.rand(); \mu; \sigma$	$Norm.rand(); \mu; \sigma$	$Norm.rand(); \mu; \sigma$
$\theta(awh)$		Uniform Dist.	

4.4 Scenario-based Decision Making Method

This method separately analyzes the parameters of P_{ep}, P_{fc}, awh, Q_d and R_d and their scenario-based changes, with the result a determination of the general distribution of annual savings that may emerge from the realization of each scenario.

Three main scenarios are set - pessimistic, likely, and optimistic - depending on the annual working hours, the economic strength of the country, and the orders the company received. Each scenario is assumed to act in compliance with the normal distribution. Based on experience, the probability of occurrence for each of these possible scenarios is assumed to act in compliance with the uniform distribution. Accordingly, the possible occurrence of each scenario over time is equally likely. Table 4.4 shows the scenarios for the running time of the CCHP system as related to the *awh* of the plant.

Regarding electricity and natural gas prices, eight different changes can be taken into account. As shown in Table 4.5, the possibilities include an increase, a decrease, or stable prices. Electricity and natural gas prices over the last 10 years have fluctuated by 13% on average, as formulated from Eq.(4.5). Thus, the change constraint of both prices is considered to be 13%. Within these constraints, electricity and natural gas prices are both assumed to act in compliance with the normal distribution, as shown in Table 4.6.

$$\triangle[P_{ep}, P_{fc}] = \frac{\mid \triangle\% P_{ep}^{n} - \triangle\% P_{fc}^{n} \mid}{n} \tag{4.5}$$

The probability of occurrence for the eight scenarios with changes in energy prices are simulated based on historical data. Upon evaluation, the correlation between electricity and natural gas prices is determined. Assessing the percentage change of the last 10

Table 4.5 : Scenarios for energy price variation.

Scenarios	P_{ep} trend	P_{fc} trend	P_{ep}	P_{fc}
current			0.0898	0.2895
EP_{s1}	⇓	—	0.0781 - 0.0898	0.2895
EP_{s2}	⇑	—	0.0898 - 0.1015	0.2895
EP_{s3}	⇑	⇓	0.0898 - 0.1015	0.2519 - 0.2895
EP_{s4}	⇓	⇑	0.0781 - 0.0898	0.2895 - 0.3271
EP_{s5}	—	⇓	0.0898	0.2519 - 0.2895
EP_{s6}	—	⇑	0.0898	0.2895 - 0.3271
EP_{s7}	⇑	⇑	0.0898 - 0.1015	0.2895 - 0.3271
EP_{s8}	⇓	⇓	0.0781 - 0.0898	0.2519 - 0.2895

Table 4.6 : The probability of occurrence for energy price.

Scenarios	P_{ep}	P_{fc}
PDF	Norm.Dist.	Norm.Dist.
μ	Scenario'	Scenario'
σ	0.0059	0.0188
$\theta(scenario)$	$Norm.rand(); \mu; \sigma$	$Norm.rand(); \mu; \sigma$
$\theta(EP)$	Triangular Dist.	

years' of energy prices, their correlation is set as 77%, as shown in (4.6). In other words, energy prices change in the same direction and intensity with a 77% probability.

$$Correl(\triangle\%P_{ep}^{n} : \triangle\%P_{fc}^{n}) = 77\% \tag{4.6}$$

In light of this, a triangle probability distribution is designed for the eight simulated energy price scenarios. Accordingly, the probability of occurrence for the seventh and eighth scenarios is set around 77%.

In the plant, heating and cooling demand is mainly a function of seasonality and weather conditions. To simulate these parameters, heating and cooling loads are put in three categories depending on changing weather conditions: moderate, normal, and extreme. The constraints of each category, defined based on historical data, are assumed to act in compliance with the normal distribution in Table 4.7. Analyzing these conditions for heating and cooling demand, nine different scenarios are generated (Table 4.8). The abbreviations *m*, *n*, and *e* refer to moderate, normal, and extreme loads, respectively, while *h* and *c* refer to heating and cooling. Lastly, the probability of occurrence for each of these demand scenarios is assumed to be equal; thus, loads are simulated based on the uniform distribution.

Table 4.7 : The probability of occurrence for energy demand.

Scenarios (Q_d)	moderate	normal	extreme
intervals	436 - 487	487 - 538	538 - 590
PDF	Norm.Dist.	Norm.Dist.	Norm.Dist.
μ	461	512	564
σ	25.5	25.5	25.5
$\theta(scenario)$	$Norm.rand()$; μ; σ	$Norm.rand()$; μ; σ	$Norm.rand()$; μ; σ
Scenarios (R_d)	moderate	normal	extreme
intervals	285 - 396	396 - 508	508 - 620
PDF	Norm.Dist.	Norm.Dist.	Norm.Dist.
μ	340	452	564
σ	55.5	55.5	55.5
$\theta(scenario)$	$Norm.rand()$; μ; σ	$Norm.rand()$; μ; σ	$Norm.rand()$; μ; σ

Table 4.8 : Scenarios for heating and cooling loads.

Scenarios	Q_d	R_d
ED_{s1}	*mh*	*mc*
ED_{s2}	*mh*	*nc*
ED_{s3}	*mh*	*ec*
ED_{s4}	*nh*	*mc*
ED_{s5}	*nh*	*nc*
ED_{s6}	*nh*	*ec*
ED_{s7}	*eh*	*mc*
ED_{s8}	*eh*	*nc*
ED_{s9}	*eh*	*ec*
$\theta(ED)$	Uniform Dist.	

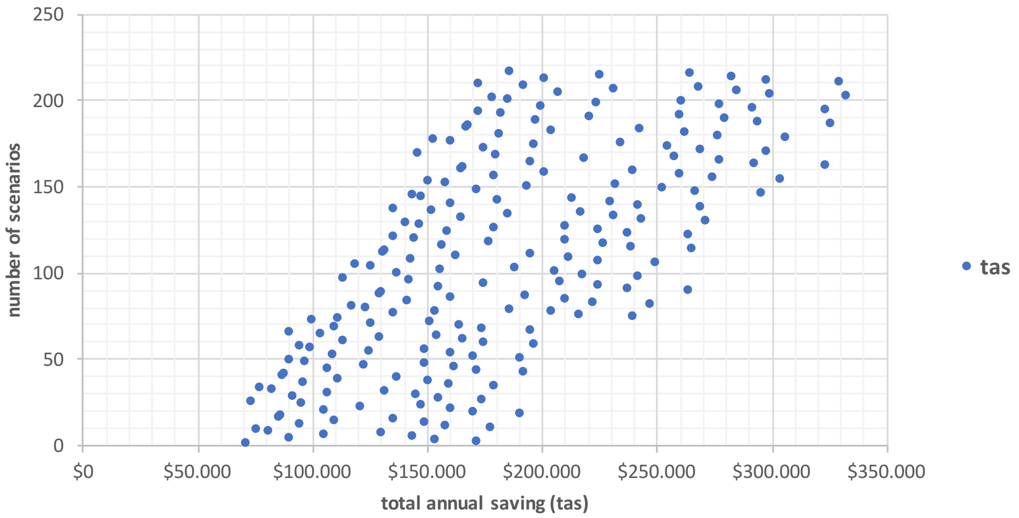

Figure 4.9 : The distribution of *tas* in scenario-based method.

Considering all the scenarios for P_{ep}, P_{fc}, awh, Q_d and R_d generates 216 different scenarios.

3 scenarios for awh x 8 scenarios for P_{ep} and P_{fc} x 9 scenarios for Q_d and R_d = 216

The distribution of the tas with a one-shot simulation, which is the most common pattern among simulations, is shown in Fig.4.9, and suggests tas will vary from \$71,822 to \$332,500. The areas where the probability of occurrence is the highest are around \$120,000 and \$220,000. As can be seen from the figure, tas will occur above \$100,000 with a high degree of probability.

In another aspect, as with the previous methods, the random changes in the parameters in all scenarios based on the defined distributions are also evaluated in Eq.(4.1). A histogram of the method after 1,000 simulations is created and overall distribution of the method, $PDF(tas)_{SM}$, has been also added in Fig.4.10 and Fig.4.11. While Fig.4.9 shows all the possible values for tas in each scenario, Fig.4.11 shows the range in which tas values may be concentrated.

4.5 Comparison of the methods

The probable tas values obtained from these methods are shown as a PDF in Fig.4.11. As this figure shows, all values comply with the normal distribution. Meanwhile statistic results of the models are shown as in Table 4.9.

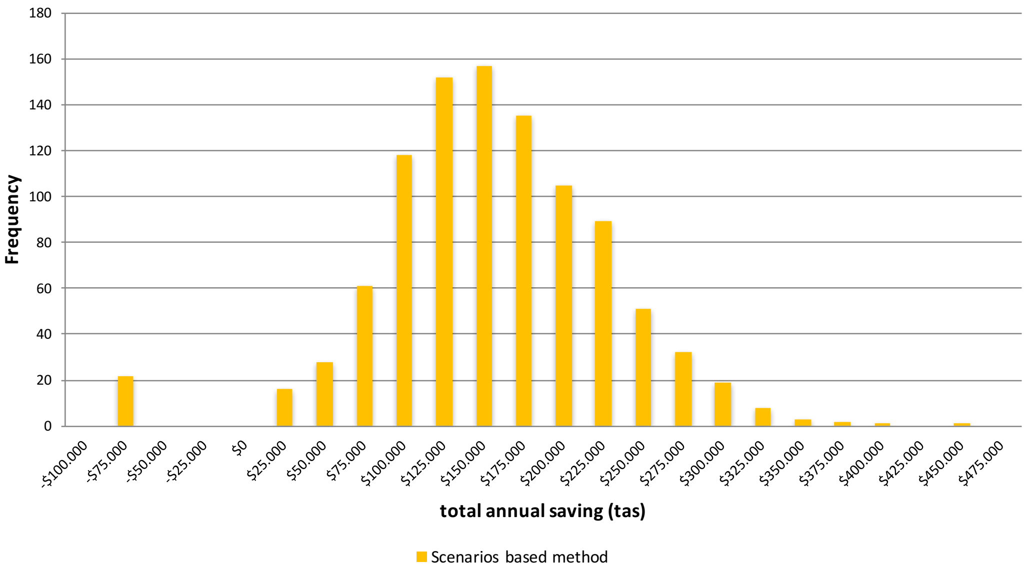

Figure 4.10 : The PDF of *tas* for Scenario-based Decision Making Method.

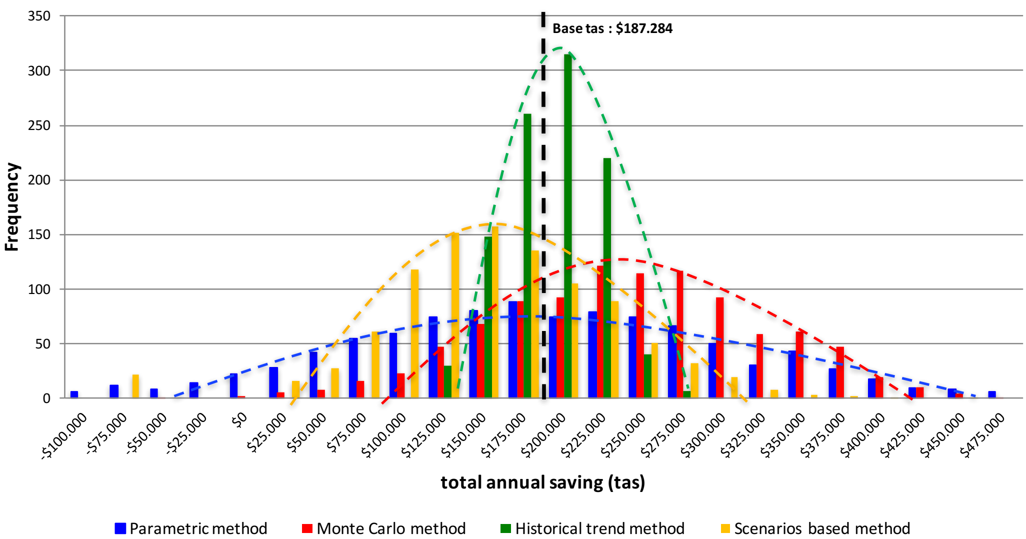

Figure 4.11 : The PDF of *tas* in four different methods.

Table 4.9 : Statistics data of methods.

Definition	Parametric	Monte Carlo	Historical trend	Scenario-based
Average	$201,555	$255,954	$202,519	$176,700
Median	$205,793	$264,686	$203,107	$170,394
Standard Deviation	$125,043	$83,080	$28,731	$71,923
Skewness	0.073	-0.366	0.127	-0.216
Kurtosis	0.082	-0.129	-0.181	1.043

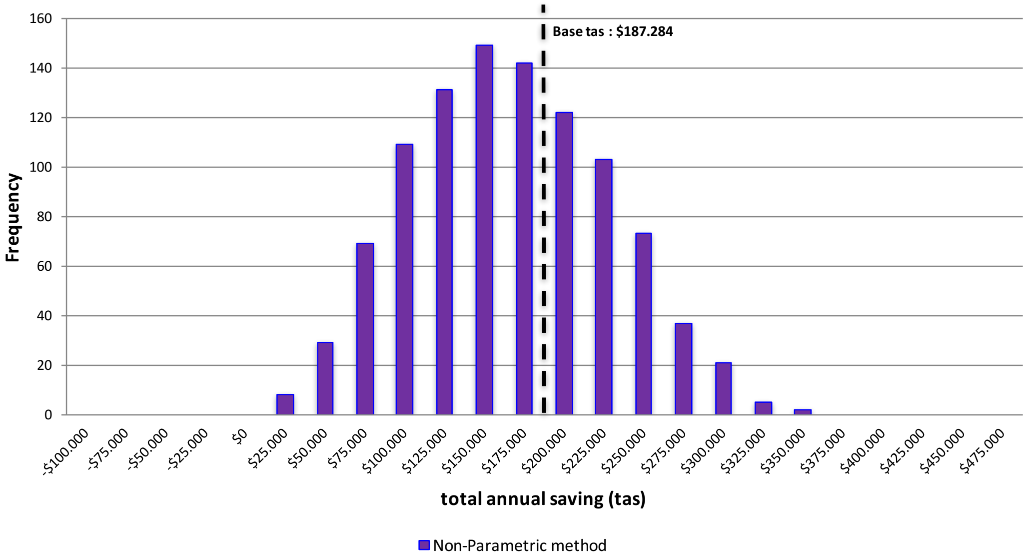

Figure 4.12 : The PDF of *tas* for non-parametric method.

The analysis showed that, the parametric method gives results across the widest range from -$100,500 to $475,000 for the *tas* value. Mean value for this method is $201,555.

The Monte Carlo method gives the highest mean value as $255,954 with *tas* range from $25,000 to $450,000, while the historical trend method gives probabilities in a narrower range for *tas* from $125,000 to $275,000. Mean value as for historical trend method is $202,519.

The scenario-based method offers a broader prediction than the historical trend method from $25,000 to $325,000 and also predicts a lower mean value for *tas* as $176,700 among all the methods.

In the first phase of the study, the system is analyzed with non-parametric method. If the system is again analyzed with non-parametric method considering the data gathered in the second phase of the study, a PDF like Fig.4.12 can be obtained.

When all the methods are again compared with non-parametic method, a PDF like Fig.4.13 is obtained.

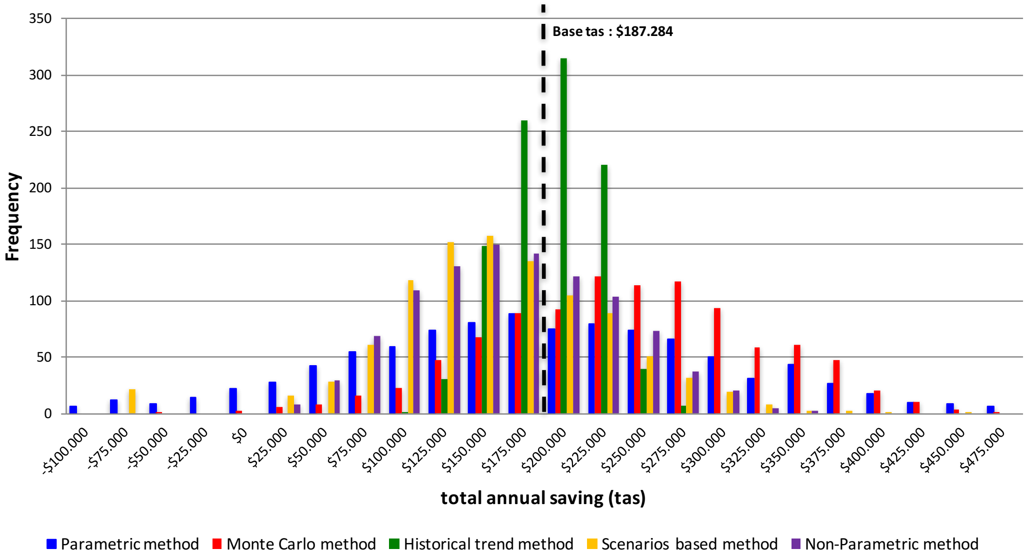

Figure 4.13 : The PDF of methods comparing with non-parametric method.

Table 4.10 : Statistics data comparison with non-parametric method.

Definition	Non-Parametric	Scenario-based
Average	$178,507	$176,700
Median	$175,939	$170,394
Standard Deviation	$61,679	$71,923
Skewness	0.172	-0.216
Kurtosis	-0.463	1.043

As can be seen in the Table 4.10, non-parametric method provides a result very close to the scenario-based method. Accordingly, specific to this study, it has been concluded that analyzing the system with non-parametric method can be substitutable with scenario-based method.

5. RESULTS AND DISCUSSION

5.1 Results and Discussion for CCHP Planning Under Uncertainty

The analyses conducted in this thesis have specifically addressed the variables that affect the economic feasibility of the investment and the uncertainties that may affect the investment any time in the system's economic life span. The main objective is to analyze all the possibilities and changes of the uncertain parameters during the life of the system to help investors see the possibility of the occurrence of the best and worst case scenario before making investment decision. Some certain criteria should be satisfied in order for CCHP power plants to be more feasible. The results concluded from this study are as follows:

The exchange rate of USD-TL and Eur-TL directly affects the pay-back period of the investment, which stems from the fact that investments are mainly quoted and funded in foreign currency in Turkey whereas total annual saving is calculated in TL. As long as TL gains value against foreign currencies, investment becomes more attractive in its economic life span of the CCHP system.

The run time of the system within a year is crucial for the amortization of the system. The more the system runs, the more profitable it becomes for the purpose of paying back the investment sooner. In this study, it is concluded that the run time should 7.200 h a year at minimum for its feasibility.

The specific gas consumption of the selected gas motors is around 0.245 Nm3/kWhe. That is to say, the electricity produced by the gas motors results in being more competitive as long as gas price is low.

The total annual saving obtained following the implementation of the system is a good indicator to evaluate the system economically. Higher electricity price render the system more profitable in terms of annual saving.

Table 5.1 : Natural gas price and electricity price ratio.

Ratio range	Risk level indicator
R h/e $\leq$ 0.30	Very Good
0.30 $<$ R h/e $\leq$ 0.40	Good
0.40 $<$ R h/e $\leq$ 0.44	Investable
0.44 $<$ R h/e $\leq$ 0.47	Risky
0.47 $<$ R h/e	Unfeasible

The ratio of electricity to gas prices provides a clear indicator of whether the CCHP investment will be feasible or not. R h/e is calculated as follows:

R h/e = ((P_{fc}/ LCV)*860)/ P_{ep}, and it can be concluded as in the Table 5.1

Thus, R h/e has been found as 0,43 for the case study one, while it has been found 0,33 in the case study two.

The selection of the PGU of the system should be handled based on the lowest electricity load of the plant with the aim of running the PGU at 100% capacity, which eventually renders the system more feasible.

Absorption cooling is fed by thermal load extracted from waste heat of gas motors. For this reason, it is very important to distribute this waste heat evenly between absorption cooling and heat demand of the plant. In the study, the optimum coverage ratio is found as 44%.

Establishing CHP or CCHP system is another important decision for investors. In this case study, it is found that CCHP system is more feasible under given loads, which are cited as thermal load between 200-400 kWh, cooling load between 450-600 kWh and coverage rate in absorption system between 25%-50%.

Decision makers tend to evaluate the investment considering DPP instead of PP particularly in a country with high discount rate like in Turkey. Lower discount rates always make the investment more attractive for investors.

B/C is another crucial indicator for decision makers. B/C should be bigger than 1 for the investable projects. According to the current economical parameters in Turkey, interest rate should be less than 7% to encourage CCHP investments.

In this study, non-parametric probability method showed that the realization possibility of the best case scenario is almost 0% under the circumstances cited above.

Based on the current values of variables, total annual saving has been calculated at 124,020 USD. At any time in the future, the realization possibility of being 124,020 USD and above for tas is around 31% in respect to non-parametric probability method. In other words, the realization possibility of being under this calculation is 69% as indicated in Fig.3.17

5.2 Results and Discussions for Stochastic Evaluation of CCHP Systems

This study aimed to use stochastic methods to estimate how the profitability of a CCHP system that is considered to be investable based on current values will change throughout its economic life. Among all the studied methods, the Monte Carlo and the historical trend methods directly take historical data as a reference. The parametric method, on the other hand, uses only the parameters of the mean and standard deviation from the historical data as a reference and thereafter assumes that all parameters will follow the normal distribution. Differing from these methods, the scenario-based method tries to determine where the objective function will be concentrated by considering all probable scenarios.

Fig.4.11 can be evaluated from two different perspectives: in terms of the range of probability of and in terms of the highest probability of occurrence for tas values in each of the four methods.

In this regard, the parametric method gives results across the widest range, offering an unclear prediction about future results. The Monte Carlo method gives the highest mean value, while the historical trend method gives probabilities in a narrower range. The scenario-based method, meanwhile, offers a broader prediction than the historical trend method and also predicts a lower mean value for tas.

As mentioned above, among all the methods applied, the Monte Carlo estimated the highest probable tas value. This is because, according to the BETA distributions, which are based on historical data of P_{ep} and P_{fc}, P_{ep} is concentrated more on the high side of the price range, while P_{fc} is concentrated more on the low side of the price range. Hence, the simulation attaches more probability to high prices for P_{ep} and low prices for P_{fc}, which is a positive result for CCHP systems in terms of profitability. Therefore, it is concluded that the possible tas value is higher in terms of the mean

Table 5.2 : Confidence level of the investment.

Methods	90% VaR of the *tas*
Parametric method	\$49,767
Monte Carlo method	\$145,440
Historical trend method	\$167,562
Scenario-based method	\$98,957

Table 5.3 : VAR() in possible *tas* intervals.

VAR()	Parametric	Monte Carlo	Historical trend	Scenario-based
tas $>$ \$200,000	9,768	7,551	28,275	22,673
\$100,000 $\leq$ tas $\leq$ \$200,000	15,717	42,557	80	1,691
\$0 $\leq$ tas $<$ \$100,000	26,196	79,849	64,712	30,203
tas $<$ \$0	43,382	91,492	64,712	49,970

value in the Monte Carlo method than the other methods, with this method suggesting it is more probable that the profitability of the CCHP system may increase over time.

For many CCHP investments, the PP preferably remains below five years. In this case study, the fact that the PP is less than five years places this investment within the critical level of \$110,000 for the *tas* value. The possibility that *tas* will exceed this level is 69.8% for the parametric method, 91.2% for the Monte Carlo method, 99.3% for the historical trend method, and 71.4% for the scenario-based method.

With regards to the 90% confidence level (c), which makes VaR (Value at Risk) = (100-c)% = 10% VaR, within all the methods, as in the Table 5.2, except for the parametric method, the possible *tas* value is estimated to be close to and above \$110,000, which is the critical level for the investment.

Evaluating the models in terms of the variance method (VAR), VAR() values for possible *tas* intervals are shown in Table 5.3. The historical trend and scenario-based methods are less volatile between \$100,000 and \$200,000, while the Monte Carlo method is less volatile over \$200,000. Accordingly, it is concluded that *tas* more probably occurs in these ranges. In the parametric method, the volatility is distributed more homogeneously over these ranges compared with the other methods.

Considering these three evaluation criteria - critical level, confidence level, and VAR method - the Monte Carlo and historical trend methods both suggest that the system's profitability will persist with a high probability, although the results may not have evaluated all risks. As a result, it is concluded that all the methods here show that this CCHP system will remain profitable with a high probability, no matter the uncertainties.

Based on these results, practical preference for each of these methods depends on the comprehensiveness of the historical data-set, its accuracy, the experience of decision-makers, and the interaction or correlation between the uncertain variables. In addition, the constraints set for these uncertain variables, their potential to violate these constraints, and whether these variables are continuous or discrete are all crucial.

It should be noted for historical trend method that if slope of regression line is relatively horizontal, the simulation can make within the constraints of the historical data. However, If the slope turned out to be relatively more vertical either in the positive or negative direction, the constraints should be determined by encompassing the possible data in the future.

Accordingly, the decision to adopt a method can be made in the following way. When there are not enough historical data, the parametric method is more suitable. When there are sufficient historical data, the Monte Carlo method is better suited to use. When historical trends are not volatile but rather linear, the historical trend method is preferable. The scenario-based method may be applied in all cases, given its ability to take all risks into account.

6. CONCLUSIONS AND RECOMMENDATIONS

Uncertainty is an important phenomenon seen in every aspect of life. Energy systems are affected by these uncertainties to a great extent. Particularly, the uncertainties like economy and weather conditions which directly affect the profitability of the energy systems are evaluated by the chaos theory.

This study contributes to the field of CCHP by providing a different point of view to investors at the stage of design and economic analysis of the systems with the purpose of seeing the impacts of seasonal load changes on the investment, the impacts of economic parameters on the profitability of the system as a part of the feasibility plan and the impacts of the possible random changes of the variables on the profitability of the investment at any time in the future.

This study has revealed that an evaluation made solely by considering the current values of the variables of the system is not sufficient to analyze the profitability of the investment. Apart from the conventional evaluation, the random changes of the independent variables at any time should be evaluated in order to see how they affect the profitability. Accordingly, it has been concluded that the deterministic evaluation is not sufficient to assess CCHP systems by its own and the stochastic evaluation gives a broader point of view in terms of overseeing all possible risks.

In light of these results, the following conclusions can be drawn. Investments in energy systems, including CCHP systems, face uncertainty. To answer whether an investment will remain profitable in the midst of these uncertainties, different methods can be applied either using past data or considering all possible scenarios. Although each method used in this study has certain advantages and disadvantages, all four methods can be used to evaluate CCHP systems at the investment stage. Since prices in almost all countries, particularly in the energy market, may not move in line with the historical trend, this study has shown that the scenario-based method is most appropriate to adopt given the comparisons and contrasts it provides.

The following evaluations should be made before the decision to invest in CCHP systems is made.

a- The correlation between natural gas and electricity prices is an important criterion. The Rh/e ratio cited in the study is essential for pre-assessment.
b- The daily and seasonal load changes of the plant and the probable impacts of these changes on the profitability of the investment should be taken into account.
c- Whether the investment of the system will be profitable in CHP or CCHP form should be decided considering the loads.
d- If the system is designed in CCHP form, cooling load should be optimally distributed between mechanical chiller (*MC*) and absorption chiller (*AC*).
e- The impact of each independent variable on profitability should be assessed by sensitivity analysis.
f- The most important variables which affect profitability should be evaluated with stochastic method.
g- The overall possible impacts of all the risks on the profitability of an investment should be analyzed by the methods adopted in this study.
h- If there is enough historical data, not only the scenario-based method but also Monte Carlo method should definitely be taken into consideration.

Another conclusion from this study can be summarized as follows: If the electricity and natural gas are priced in local currency and the investment is made in foreign exchange terms, this will increase the probability that the risks of exchange rate and interest will affect the investment negatively.

If the electricity and natural gas is priced in foreign exchange terms, which means there is not risk of exchange rate and interest, CCHP system will probably be profitable and remain so in the load ranges cited in this study.

The methods mentioned in this study are already used in statistics field and finance sectors. However, it is the first time that all of these methods are used in the feasibility of a CCHP system as a whole by providing a general point of view and the opportunity to evaluate the risks for CCHP systems which encompass many uncertainties in the investment phase.

In addition, this study suggests that the evaluations made and the ways these methods are used in this case can be adopted in many other energy projects.

In work to follow, the mostly likely value of *tas* can be forecasted for later years, drawing on support from the methods studied above. As a part of further studies, developing a software that will enable a stochastic evaluation for all energy systems is also aimed with a more general approach.

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