ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

FINDING THE BEST LOCATIONS FOR PHOTOVOLTAIC PANEL INSTALLATION IN URBANIZED AREAS

M.Sc. THESIS

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Department of Geomatics Engineering

Geomatics Engineering Programme

DECEMBER 2017

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

KENTSEL ALANLARDA FOTOVOLTAİK PANEL KURULUMU İÇİN EN UYGUN KONUMLARIN BELİRLENMESİ

YÜKSEK LİSANS TEZİ

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To my parents,

FOREWORD

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December 2017

Hande Mahide YEŞİLMADEN
(Geological Engineer)

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ABBREVIATIONS

AC **:** Alternative Current
AHP **:** Analytic Hierarchy Process
ASCII **:** American Standard Code for Information Interchange
ASR **:** Area Solar Radiation
BIPV **:** Building Integrated Photovoltaics
CSP **:** Constrating Solar Power
DC **:** Direct Current
DEM **:** Digital Elevation Model
DNI **:** Direct Normal Irradiance
DSM **:** Digital Surface Model
DSS **:** Decision Support System
GHI **:** Global Horizontal Irradiance
GIS **:** Geographic Information System
LiDAR **:** Light Detection and Ranging
MDCM **:** Multi-Criteria Decision Making
OECD **:** Organization for Economic Co-operation and Development
PV **:** Photovoltaic
RES **:** Renewable Energy Systems
Si **:** Silicon

SYMBOLS

$AngIn_{\theta,\alpha}$: Angle of incidence
Dif_{tot} : Diffuse radiation
Dir_{tot} : Direct radiation
$Dir_{\theta,\alpha}$: Direct insolation
D_{ur} : Time interval
G_a : Azimuth angle of the surface
$Global_{tot}$: Global radiation
G_z : Zenith angle of surface
P_{dif} : Diffuse global regular radiation flux
R_{glb} : Global normal radiation
S_{Const} : Solar constant
$SkyGap_{\theta,\alpha}$: Gap fraction for the sky sector
$SunDur_{\theta,\alpha}$: Time duration
$SunGap_{\theta,\alpha}$: Gap fraction for the sun map sector
α : Azimuth angle
β : Transmissivity
θ : Zenit angle
φ : Latitude

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FINDING THE BEST LOCATIONS FOR PHOTOVOLTAIC PANEL INSTALLATION IN URBANIZED AREAS

SUMMARY

Energy is an indispensable necessity in today's conditions. Social and economic development is proceeding in parallel with energy production. At the same time, the resource used in energy production also influences this progress. The air pollution is created by the widespread use of highly efficient fossil energy fuels has negative impacts on developments, especially social development. The use of renewable energy sources should be increased by reducing the use of fossil fuels to achieve sustainable development.

Electricity production can be divided into two according to their sources. Those are renewable energy plants and fossil fuel plants. The use of renewable energy sources should be increased to reduce the effects of greenhouse gases and to achieve sustainable development. The urban area is places where the human population is intensive, and therefore energy consumption is high. With the solar energy plants that can be installed spare area of an urban area like rooftops, it is possible to reduce the electric power transmission costs and the air pollution caused by carbon dioxide emissions.

Rooftop solar photovoltaic applications are classified as a small-scale source of electricity generation. Large-scale electricity plants are generally constructed outside of the urban area. Hydroelectric plants need to be located near rivers with high water flow velocity; nuclear stations need to be near huge water resources to provide cooling of the system and wind turbines are required to be in upland locations with high wind potential. Fossil fuel energy stations produce emissions so they might be located away from residential area. As it is seen, there are binding barriers that prevent most power plants from being installed into the urban area. Solar photovoltaic applications are independent as to other electricity production plants. It is because of the source of electricity production. The Sun is covering all around the Earth, and its efficiency of incoming radiation depends on latitude. In the same latitude, the effect of solar radiation might be considered the same as the center of the city or rural area. This functionality of installation is essential to make use of an opportunity the spare area of rooftops.

Geographic information systems have the ability to analyze spatial data by associating it with attribute data. The ideal way expanding the use of solar energy in city centers will be geographic information systems. In order to maximize utility from solar energy, it is necessary to identify the location that can be used efficiently. This location can be identified with orientation and tilt angle. Other factors affecting productivity are solar radiation and photovoltaic type. Geographic information systems can combine all the factors mentioned above to measure the most efficient location for the rooftop-PV application. This study aims to come up with a Geographic information systems-based

model to estimate the most efficient and usable idle locations of the rooftops to generate electricity by photovoltaic panels.

The weighted overlay analysis is one of the Multi-Criteria Decision Making methods used in this study. The Geographic Information Systems tools enabled the location-based weighted overlay process. This analysis based on scores and weighted percent of the factors. The primary factor as input for rooftop photovoltaic applications, slope, aspect and solar radiation. The fundamental inputs for analysis were point cloud data in ASCII format and rooftop area in vector format. The model is created with ModelBuilder extension of ArcGIS 10.X. The used analyses were selected from the toolbox and combined in ModelBuilder. There is an interface for the user to select input and output locations. The moderate analyses stay in the background; only the results share with the user. In the model, first, the roofs were classified two class according to their average slope degree. The feasibility calculation includes only pitched roofs. For pitched roofs, the slope, aspect and solar radiation analyses were implemented and reclassified as their significance level. The results of reclassification were processed weighted overlay with their influence percent. The flat roofs examined only to find the plain regions. Only the slope analysis and the slope reclassification was implemented to find suitability areas. The reason of the differences of the analyses are the cost of installations. It is anticipated that extra cost will be required for providing proper slope and aspect on flat roofs.

As feasibility analysis, according to the building ID and its suitability ranks, the suitability areas were calculated. The 270 Wp photovoltaic panel was used for energy calculations. The price of a single module has been learned from the manufacturer as $ 146.1. The feasibility analyses were made considering that the panels were installed in areas with the high rank of suitability. The results of suitability analysis made on the pitched roof of 7 units; the total available space at high suitability rank is 653.25m^2, making up 24% of all eligible areas. The number of panels to be used is calculated as 335 pieces. 17% to 33% of each roof is in high suitability. The plain areas that can be done installation different from the structural shape of rooftop in flat roofs are 60% - 70% of the surface. The feasibility results were shown, in one building with 105 m^2 roof area, could cover 70% of electricity consumption from PV rooftop applications.

KENTSEL ALANLARDA FOTOVOLTAİK PANEL KURULUMU İÇİN EN UYGUN KONUMLARIN BELİRLENMESİ

ÖZET

Enerji devriminden beri enerjiye duyulan ihtiyaç her geçen gün artmaktadır. Gelişen toplumlarda yaşam standartlarında kaliteyi sağlamak enerji ile üretimi ile doğrudan bağlıdır. Günümüzde enerji ihtiyaçlarının karşılanması kömür, doğalgaz gibi fosil yakıtlara dayanmaktadır. Fosil yakıtlar tüketime bağlı rezervi azalan sonlu yakıtlar olarak tanımlanabilir. Bu yakıtların ürettikleri enerji yüksek ve göreceli olarak kurulum maliyetleri yenilenebilir enerji sistemlerine göre uygundur. Fakat çevreye olan olumsuz etkileri, olumlu olarak görülen etkileri ile kıyaslanarak değerlendirilmelidir. Havadaki sera gazı emisyonunu arttırarak küresel ısınmaya ve hava kirliliğine etkisinin yadsınamayacak kadar çok olduğu çeşitli çalışmalarda belirtilmektedir. Sosyal ve ekonomik kalkınma teknoloji ve dolayısıyla enerji ile bağlantılı olarak gerçekleşebilmektedir. Kalkınmayı durduramayacağımızdan, enerji üretim şekline doğa dostu alternatifler kullanarak kalkınırken çevreye saygılı, sürdürülebilir kalkınma gerçekleştirebiliriz. Sürdürülebilir kalkınma, temiz enerji denildiğinde dereye yenilenebilir enerji kaynakları girmektedir. Güneş, rüzgar, jeotermal enerji, hidroelektrik, dalga, biyokütle yenilenebilir enerji kaynakları olarak sıralanabilir.

Bu çalışmada yenilenebilir enerji kaynaklarından güneş, doğrudan güneş enerjisini elektriğe dönüştüren hücrelerden oluşan olan fotovoltaik teknolojisi ele alınmıştır. Fotovoltaik hücreler yarı iletken malzemeler olup, seri veya paralel bağlanarak voltaj ve akım üretirler. Monokristal silikon, polikristal silikon, silikon ve ince film teknolojileri ticari olarak kullanılan fotovoltaik materyalleridir. Silikon temelli hücreler yaygın olarak kullanılmaktır. Bunu başlıca nedenleri, silikonun kolaylıkla temin edilebilmesi ve yüksek enerji dönüşümü yeteneğine sahip olmasıdır. Bu çalışmada fizibilite analizleri yapılırken, hesaplamalarda silikon polikristalin panel kullanılmıştır.

Enerji üretimi gerek enerji kaynağının yeri ve kurulması gereken tesisin büyüklüğü bakımında gerekse insan sağlığına olan olumsuz etkileri azalmak adına şehir merkezlerinden uzağa kurulmaktadır. Bu tesislerde üretilen enerjinin iletim hatlarıyla taşınarak kullanımı sağlanmaktadır. Enerjiye en çok ihtiyaç olan şehir merkezlerinde ise esas sorun kurulum yapılacak alan kısıtıdır. Nüfus artışına bağlı bina yapımının arttığı düşünüldüğünde, boş alan olarak inşaa edilmiş binaları değerlendirmek gerekmektedir. Binalarda göze çarpan en atıl alanlar ise çatılar ve bina cepheleridir. Fotovoltaik teknolojinin ve güneşin enerji kaynağı olarak kullanılmasıyla, bu alanlar değerlendirilerek üretilen enerjinin üretildiği yerde tüketilmesi sağlanabilir. Aynı zamanda fosil yakıtların kullanımdan elde edilen enerji üretimini düşüreceği için çevreye olan zararı da azaltacaktır.

Çatıların panel kurulumuna uygun boş alan olarak alındığı bu çalışmada esas değinilmek istenen nokta çatılardaki hangi bölgelerin ne kadar uygunluğa sahip

olduğunun derecelendirilmesidir. Böylece doğru yerlere kurulum yapılarak, pahalı bir teknoloji olarak görülen fotovoltaik sistemlerden maksimum verimde fayda sağlanabilir.

Çatıların konumsal olarak değerlendirilmesi işlemi, konuma dayalı karar vermeyi süreçlerini destekleyici, depolama, analiz, veri toplama araçlarını içeren Coğrafi Bilgi Sistemleri'nden faydalanılarak yapılmıştır. Coğrafi verilerin temel bileşenleri mekansal veriler ve özniteliklerdir. Mekansal veri, Dünya üzerindeki coğrafi referanslı veriler demektir. Öznitelik veri ise mekansal veriyle bağlantılı bilgi anlamına gelmektedir. Mekansal verinin vektör ve raster olmak üzere iki tür gösterimi vardır. Raster veri, piksellerden oluşur ve her bir piksel konumsal bilgiye sahiptir. Vektör veri, nokta, çizgi ve poligon olmak üzere koordinatlı geometrik unsurlardan oluşur. Bu çatı alanları vektör veri tipinde poligon olarak, raster veri tipinde ortofotolardan sayısallaştırılmıştır. Vektör veri tipinde nokta bulutu verisinden, raster veri formatında Sayısal Yüzey Modeli (SYM) oluşturulmuştur. CBS'de uygulanan mekansal analizler, ham verilerin faydalı bilgiler haline getirildiği süreçlerdir. Kullanılan mekansal analiz işlemleri; yeniden sınıflama, çakıştırma, komşuluk ve yüzey analizleri olarak temel sınıflara ayrılabilir. Yeniden sınıflandırma işlemi, hücre değerlerini alternatif değerlere göre yeniden sınıflandırır veya mevcut değeri değiştirir. Çakıştırma işlemleri, mekansal ve öznitelik verileri iki veya daha fazla uzaysal veri katmanı ile birleştirerek yeni unsurların oluşturulmasını sağlar. Çakıştırma analizi, belirli bir kullanıma uygun yerleri veya risklere duyarlı yerleri bölgeleri belirlemek için sıklıkla kullanılır. Komşuluk analizleri, belirli bir bölgedeki komşu alanların özelliklerini göz önüne alarak işlem yapmayı sağlar. Bunlar tampon ve enterpolasyon işlemlerini içerir. Tampon işlemi, orijinal nesnelerden belirli bir mesafede tampon bölge oluşturma işlemi olarak tanımlanabilir. Yüzey analizleri, eğim ve bakı işlemlerini içerir. Eğim analizi, arazinin eğiminin büyüklüğünü belirtmek için kullanılır ve eğimin yönünün belirlenmesi bakı analizi ile gerçekleştirilir.

Çok kriterli karar verme yöntemleri uygulanabilir alternatiflerden çoklu kriterlere ve çelişen hedeflere dayalı mümkün olan en uygun alternatifleri seçmeyi sağlayan bir prosedürdür. Karar verme mekanizması olarak çok kriterli karar verme metotlarından ağırlıklı çakıştırma yönteminden yararlanılmıştır. Puanlama ve ağırlıklı yüzdelere dayalı bu sistemde, her bir faktöre sonuca etkisine göre yeni değerler atanır. Atanan bu değerler coğrafi bilgi sistemleri tabanlı araçlar yardımıyla, her bir faktörün sonuca etkisi yüzde olarak belirlenir ve çakıştırma işlemi gerçekleştirilir. Sonuç ürün olarak uygunluk derecelerine göre sınıflanmış tek bir katman elde edilir.

Fotovoltaik sistemlerin kurulumu için uygun yer seçiminde hesaplanması gereken faktörler; çatı alanı, çatının eğimi, bakısı ve güneş radyasyonu. Girdi olarak kullanılan temel veri ASCII formatında fotogrametrik yöntemlerle elde edilmiş nokta bulutudur. Çatı alanları ortofotodan sayısallaştırılmış olup, her bir binaya bir ID atanmıştır. Analizler yapılırken girdilerin ve çalışma alanının seçildiği bir ara yüz oluşturulmuş olup, analizlerin her adımı çıktı olarak kullanıcıya sunulmamaktadır. Amaç kullanıcının sonuç ürünü görmesi, ara analizlerin gösteriminin isteğe bağlı yapılmasıdır. Model oluşturulurken ArcGIS 10.2 yazılımının analiz araçları kullanılmıştır. Hesaplamaları yapmak için kullanılması gereken analiz araçları zincir şeklinde birbirine eklenerek oluşturulmuştur. Bu işlemler için yazılımın ModelBuilder aracı kullanılmıştır. ModelBuilder, mekansal analiz iş akışları oluşturmak için görsel bir programlama dilidir. Model de ilk olarak nokta bulutu verisinden, çatı tipi sınıflaması yapmak için eğim analizi yapıldı. Ortalama eğimi 0-25 derece arasında olan çatılar düz, 25 dereceden yüksek olan çatılar eğimli çatı olarak sınıflandırıldı. Çatı

tipine göre analizler iki ayrı koldan ilerleyip, iki ayrı uygunluk haritası oluşturuldu. Nokta bulutundan 2 farklı SYM oluşturuldu. Eğim ve bakı analizleri için çatı alanlarına göre kesilmiş SYM ile güneş radyasyonu hesabı yapmak için tüm veri SYM'ne dönüştürüldü. Çatı alanları kadar kesilen SYM'lerden eğim ve bakı analizleri yapıldı. Eğimli çatılar için, eğim analizi sonuçları 4 sınıfa ayrıldı. Eğimin en uygun olduğu değer, çalışma bölgesinin enlemidir. Bu nedenle, çalışma bölgesinin enlem derecesini içeren aralık en uygun değer olarak seçildi ve bu aralığa 4 değeri atandı. 60 dereceden yüksek eğimler kuruluma uygun değil şeklinde sınıflandı ve 1 değeri atandı. 0-30 derece arası 3, 45-60 derece aralığına ise 2 değeri atanarak yeniden sınıflama işlemi gerçekleştirildi. Bakı analizinde çatıların yönelim yönlerine göre sınıflama yapıldı. Güney, güney doğu, güney batı yönleri en uygun yönler olarak seçilirken, kuzeye bakan yüzeyler en az uygun olan yönelimler olarak seçilerek, bakı analizi sonuçları da 3 sınıfa ayrılacak şekilde yeniden sınıflandırma işlemi gerçekleştirildi. Eğimli çatılarda karar verme analizi olan ağırlıklı çakıştırma işlemine girecek olan son analiz olarak güneş radyasyonu hesaplamaları yapıldı ve analiz sonuçları 3 sınıfa ayrıldı. Bu çalışmada güneş radyasyonun yüksek olduğu bölgeleri hesaplamak için radyasyon analizi yapılmıştır. Elektrik üretime doğrudan etkisi hesaplanmayacaktır. Ağırlıklı çakıştırma işleminde, en yüksek yüzde bakıya verilmiş olup, eğim ve güneş radyasyonu eşit yüzde de değerlendirilmiştir. Bakının ağırlığı %60 olup, eğim ve güneş radyasyonu %20'şer ağırlığı paylaşarak çakıştırma hesaplaması gerçekleştirilmiştir. Bu işlemin sonucunda eğimli çatılar için uygunluk haritası oluşturulmuştur. Bir adet panelin alanı yaklaşık $2m^2$'dir. Kurulum alanlarının hesaplanması için, alanı panelin kapladığı alandan küçük çatı segmentleri seçilip çıkartılarak, her bir çatı için uygunluk derecelerine göre kurulum yapılabilir alanlar belirlenmiştir. Düz çatılarda durum biraz daha farklıdır. Düz çatılarda sadece eğim analizi yapılmış olup, düz alanlar belirlenmiştir. Verimliliği arttırmak için gerekli eğim ve yönelimin sağlanması için çatının halihazırdaki yapısının dışında bir yerleşim gerekecektir. Bu yüzden fizibilite analizlerinde düz çatılar değerlendirilmeyecektir, çünkü panel yerleşimin nasıl yapılacağına dair araştırma bu çalışmanın kapsamına girmemektedir.

Fizibilite çalışmalarında 270 Wp panel üzerinde hesaplamalar yapılmış olup, tek bir modülün fiyatı 146,1 $ olarak üreticiden öğrenilmiştir. Panelin standart koşullardaki elektrik üretimi değerleri fizibilite çalışmalarında kullanılmıştır. Bu yüzden uygunluk derecesi yüksek çıkan alanlara panel kurulumu yapıldığı düşünülerek fizibilite hesaplamaları yapılmıştır. 7 adet binaya ait eğimli çatıda yapılan uygunluk analizi sonuçlarına göre; yüksek uygunlukta toplam kullanılabilir alan $653,25m^2$ olup, tüm uygun alanların %24'ünü oluşturmaktadır. Kullanılması gereken panel sayısı 335 adet olarak hesaplanmıştır. Her bir çatının yüksek uygunluğa sahip alanı %17 - %33 aralığında çıkmıştır. Düz çatılarda kurulum yapılabilecek düz alanlar çatıların %60 - %70'ni kapsamaktadır. 65 daireden oluşan bir bina için diğer binalara göre daha detaylı fizibilite hesaplamaları yapılmıştır. Temmuz ayındaki elektrik tüketimi 3208 kWh'dir. Temmuz ayındaki güneşlenme süresi 10,72 saattir. 105 m^2'lik çatı alından, 52 tane panel yerleştirileceği düşünüldüğünde 25 kWp kurulu gücün aylık üretiminin 4515 kWh olacağı hesaplanmıştır. Fakat unutulmaması gerekir ki, panellerin verimliliği, gelen güneş radyasyonuna bağlı gün içerisinde değişmekte olup, iletimden kaynaklı olarak da kayıplar yaşanmaktadır. Bunlar göz önüne alınarak %50 verimlilikle elektrik üretildiği düşünülürse %70 oranında binanın elektrik tüketimini karşılayabilmektedir.

1. INTRODUCTION

The energy demand has been rapidly increasing all over the world since the industrial revolution. The energy is essential for growing populations of the civilized cities to maintain the quality of the living standards. The increasing energy demand has mostly been supplied by finite energy sources such as fossil fuels as coal, oil or natural gas reserves. However, the use of fossil fuels has the critical negative aspects to the environment as accelerating global warming and air pollution due to increasing greenhouse gas emissions. According to International Energy Agency (IEA), World Energy Outlook Special Report (2015) "Greenhouse gas emissions from the energy sector represent roughly two-thirds of all anthropogenic greenhouse-gas emissions and carbon dioxide emissions from the sector have risen over the past century to ever higher levels." Another important point mentioned in the IEA report is "to preserve a 50% chance of limiting global warming to 2°C, the world can support maximum CO_2 emissions "budget" of 3000 gigatonnes (Gt) (IPCC, 2014), of which an estimated 1970 Gt had already been emitted before 2014" (IEA, 2015).

Potential solutions to current environmental problems have identified along with Renewable Energy Sources (RES) and technologies since they can provide a reliable and sustainable energy supply almost indefinitely. RES is considered suitable for local and regional applications. Therefore, RES is the economic power supply for small isolated settlements and potentially available for use in urban areas.

Hydroelectricity, geothermal, solar photovoltaic, solar thermal, ocean, wave, wind, solid biofuels, biogases, liquid biofuels, and waste are renewable energy products (IEA 2016). According to the Renewable Energy & Environmental Technologies Investment report published by Investment Support and Promotion Agency of Turkey (ISPAT), installed energy supply capacity of Turkey was 57,058 MW in 2012 and renewables including waste, geothermal and wind accounted for only 5% of the installed capacity, wind energy being the highest with 2,261 MW (ISPAT, 2013). When the RES availability and use in urban areas is considered, it is obvious that one

of the most suitable potential source is the solar energy due to the available space requirement.

Improvements of the solar photovoltaic system, the direct conversion of sunlight into electric power by a solid-state device, has progressed rapidly since the launch of the first satellite in the 1950s. Developments in Photovoltaic Technology paved the way for usage of Solar Energy (Dincer, 2000). As a result, several types of energy generation systems have been implemented for solar energy supply on building rooftops and facades or at installed solar farms.

One of the most crucial concerns of RES management is selecting the sites available for an efficient energy supply. In this context, site selection procedures are applied including suitability analysis using a variety of data sources such as spatial data in which weights are assigned to geographical criteria. The locations with the highest solar energy potential are not always feasible sites for installing energy plants. The efficiency of the installed plant is not only related to energy potential but also has a strong relationship with the requirements of meteorology, economics, environment, and society. The use of idle spaces in the roof is one of the advantages of small-scale panel applications. This kind of panel installation is a practical solution not only to reduce energy costs but also to produce electricity in a more sustainable way (MacDonald, 2014).

Geographic Information System (GIS) integrates data acquisition, storage, analysis, and management tools in applications that solve problems related to geospatial information (Chen, 2010). GIS allows working with more than one spatially defined variables and enables the use of Multi-criteria decision-making methods (MCDM). The purpose of these methods is to analyze a number of alternatives in the light of multiple criteria and conflicting objectives (Sánchez-Lozano et al., 2013). This study focused on a model with the combination of GIS and MCDM in order to obtain the optimal placement of rooftop photovoltaic systems.

1.1 Aim and the Scope of the Thesis

Power plants are often installed away from settlements, depending on the size of the plant, human health, and source of energy. The in situ energy production is benignant for the transmission expenditure. When the Sun is preferred as an energy source, the

idle areas within the urban could be included in energy production. At this point, it is essential to highlight the fact that the Sun is an infinite energy source. Solar photovoltaic panels and selecting suitable areas are the critical parameters in solar energy production. Photovoltaics convert the sunlight into electric power by a solid-state device (Dincer, 2000). Suitable area selection could be implemented adequately with GIS. The purpose of this study is to create a Geographic Information System (GIS) based-model that will enable the solar photovoltaics to be installed in the urban areas and provide electricity generation with maximum benefit. The study also includes the feasibility analysis of the selected area. Area calculations of the zones that correspond the eligibility criteria are done and the number of panels to be installed is calculated. Feasibility analysis is performed by calculating the electric energy that can be produced under normal circumstances of the panels to be installed.

1.2 Research Outline

The ultimate need for renewable energy, the Geographic Information System (GIS) technology, and the objective of this study was introduced in the first chapter. In the second chapter, previous works of the scholars and the detailed information about the GIS was stated. Moreover, an extensive amount of information was given about the solar energy. The applied methodology was defined in section three, and in section four, this methodology was implemented in the selected pilot area. In the last section, the obtained results were analyzed, and the study was concluded by discussions and suggestions.

2. SOLAR ENERGY AND GIS

2.1 Solar Energy

Sun is the primary energy source of the Earth, and solar radiation is utilized for electricity generation and hot water production. Solar photovoltaic is used to generate electricity by photovoltaic cells. Solar thermal is for hot water production by flat plate collectors and electricity generation by solar thermal-electric plants (Renewables Information, IEA 2016).

2.1.1 The situation of solar energy

Renewables are the world's second-largest source of electricity supply after coal. The renewable energy sector is 70% of total electricity generation investment in 2015 (IEA, 2016b). The investment was separated wind power (37%), solar photovoltaic (PV) (34%) and hydropower (20%). "China led global investment in renewables-based generation in 2015 ($90 billion, more than double its investment in fossil fuel-based generation), followed by the European Union ($56 billion, led by wind), the United States ($39 billion, led by solar PV and wind) and Japan ($30 billion, mainly solar PV)." (IEA, 2016b).

In 2015, solar energy performed about 25% higher than the previous record year with 49GW. Germany had the most extensive installed solar PV capacity, but in 2015 China added more than 15GW of installed solar PV capacity and surpassed Germany. In the same year, The United States saw a significant increase in solar PV capacity (7.3 GW), The government of Japan saw the addition of 11 GW of solar PV capacity, The United Kingdom saw the highest increase in capacity in Europe with 3.7 GW. Germany, the country set the global progression for solar PV expansion, was in a downtrend (IEA, 2016b).

As seen in Figure 2.1 Solar PV growth 44,1% per annum since 1990 to 2015 and the second highest growth after liquid biofuels in the Organization for Economic Co-Operation (OECD) includes Turkey. The OECD produced 174.5 TWh of PV electricity in 2015, 7.1% of its total renewable electricity production. Leading

producers of solar PV electricity generation were Germany with 38.4 TWh, Japan with 36.0 TWh, Italy with 25.2 TWh, the United States with 24.1 TWh, and Spain with 8.3 TWh. This production is equal to 75.7% of the PV electricity in the OECD (IEA, 2016a).

Without a doubt, usage of solar energy creates new job opportunities. Around 8.1 million people will be employed in the world's renewable energy sector, and the largest labor force in renewable energy is solar PV, then followed by biofuels and wind (IEA, 2016b)

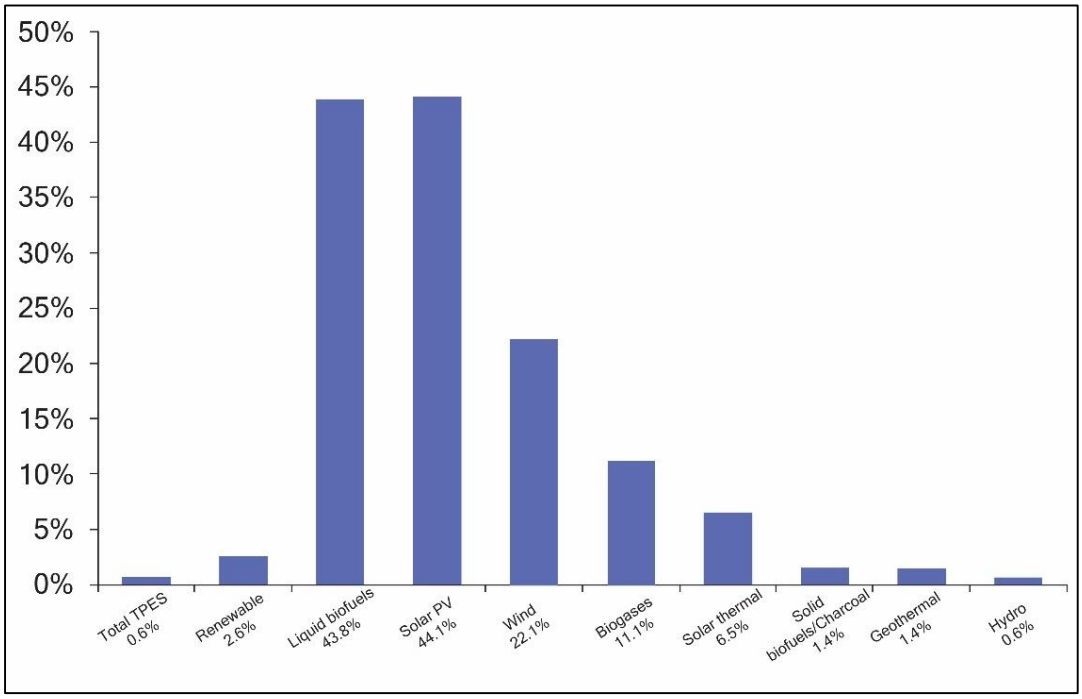

Figure 2.1 : Annual growth of renewable supply from 1990 to 2015 in OECD total adapted from (IEA, 2016a).

Technological developments changed the idea about the costs of renewable energy applications. In roughly five years, the global average capital cost has fallen approximately 60% for solar PV. In 2015, global average capital costs for utility-scale solar PV projects completed $1700/kW[1]. Germany, China, and India had the lowest costs market while the United States, South Africa, and Japan had higher cost markets (EIA, 2016b).

Solar availability in China is 2200 h of sunshine and annual solar radiation in excess of 1627 kWh /m^2 (Şenkal and Kuleli, 2009). As it is seen on the map Figure 2.2, China

1 Solar PV capital costs are submitted in direct current (DC) terms, referring to the rated capacity of the solar panel array.

has almost same solar radiation value with Turkey. On the contrary, Germany has much lower radiation values. Overall, leading countries on the electricity generation from solar energy are China and Germany.

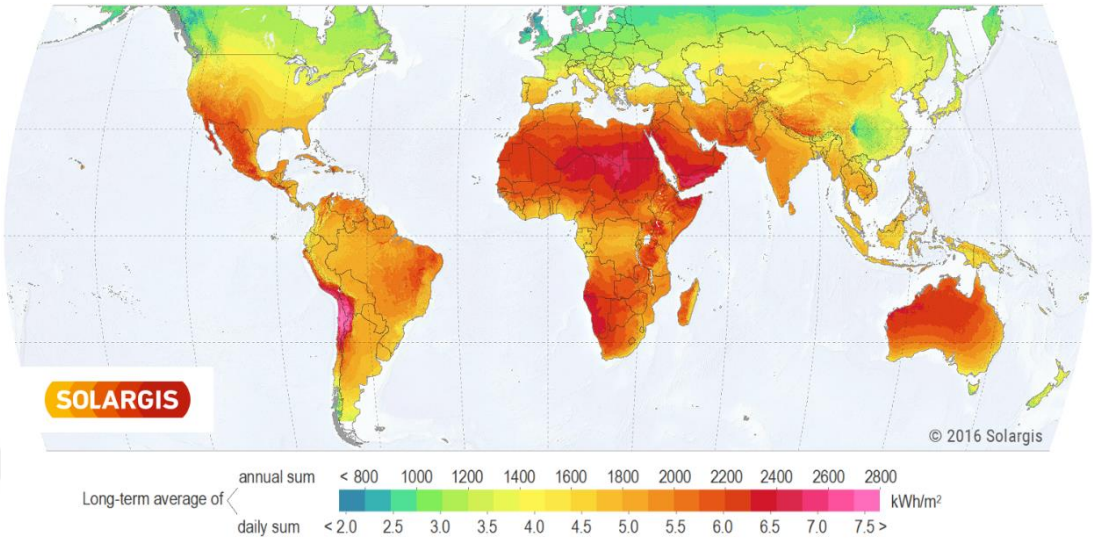

Figure 2.2 : Global horizontal irradiation map (Url-6).

2.1.2 Solar energy applications

Solar energy plants are installed as solar farms built on vast lands and rooftop installations on the individual buildings in settlement areas. Photovoltaic (PV) modules are feasible to use any surface of buildings due to the cells or a laminated structure of the modules. PV in buildings is known as the acronym of Building-integrated photovoltaics (BIPV). PV installations can be applied on be facades or rooftops. The main barrier in front of the usage of PVs at buildings was the expensive installation cost; one can expect if there is any decrease in cost, PVs in buildings will be spread in the construction sector (Frontini et al., 2013). Solar farms are known as the large-scale applications. The differences between rooftop applications and solar farms are the generated energy capacity and installation parameters. The main installation parameters are the buffer analysis in order to fulfill the security, social and environmental requirement for solar farm applications (Uyan, 2013). Characterization of the rooftop geometry is the fundamental requirement for rooftop PV site selection process (Boz et al. 2015).

The thermal solar panels generate thermal energy from incoming solar radiation which is common in Turkey (Melikoglu, 2013). The efficiency and price of thermal solar panels are lower than PV panels.

The Concentrating Solar Power (CSP) systems include mirror or lenses and tracking system. The incoming solar radiation is focused on one point to generate thermal heat. The produced concentrated heat is the source of a conventional power plant (Sharma, 2011).

2.2 GIS in Theory and Practice

2.2.1 Data types of GIS

According to the National Center for Geographic Information and Analysis of the USA (NCGIA) Geographic Information System (GIS) can be defined as a hardware and software system, designed for the capture, storage, analysis, modeling and data presentation, spatially referenced, for the resolution of complex problems of planning and management (Sánchez-Lozano et al., 2013). Fundamental components of geographic data are spatial data and their attributes. Spatial data indicates the geographically referenced features on the Earth. Attribute data means, the information linked to the spatial data. There are two types of spatial data representation, which are vector data and raster data. Raster data is stored in a two-dimensional matrix of uniform grid cells, all with the same size (Malczewski, 2004). Each cell is called pixel and has specific geographic location information. Vector data format is represented by geometric features of coordinates and comprised of data elements such as points, lines, and polygons. The attribute data is defined as the text data linked to the vector data.

2.2.2 GIS operations and functions

The analyses applied in Geographic Information System (GIS) are considered as the processes by which the raw data is turned into useful information. The fundamental operations of GIS include operations on measurement, re-classification, overlay, and neighborhood. Measurement operations include length, area, or shape properties of objects and distance or direction relationships between pairs of objects. Raster-based systems allow the user to generate measurements from a selected pixel. In vector systems calculations are automatically generated in attribute tables.

Reclassify operation reclassifies or changes cell values to alternative values using a variety of methods. This operation aims to simplify the output data to assist in interpretation (Url-3)

Overlay operations result in the creation of new features with combining spatial and attribute data with the two or more spatial data layers. Overlay operation is applicable to vector and raster data types. Overlay operation might overlay multiple feature classes to combine, erase, modify, or update spatial features, resulting in a new feature class (Url-5). Overlay in the raster is the result of overlaid two raster layers with the attributes of each cell are combined according to a set of rules. Map algebra is based on overlay calculations include arithmetic expressions which classify spatial data into basic classes (Longley et al. 2005). Overlay analysis is often used to find locations suitable for a particular use or susceptible to some risk.

Neighborhood operations consider the characteristics of neighboring areas around a specific location. They include buffering and interpolation. Buffering builds a new object or objects zone around the features with a specified distance of the original objects. Buffering is possible in both raster and vector formats. In the raster data set, it is calculated that the classification of cells is outside of the buffer or inside of the buffer. The buffering of the vector data set is created a new set of objects. Interpolation is a prevalent method to estimate the value of a continuous area where the area has not actually been measured (Longley et al., 2005).

Surface analyses include slope and aspect processes. Input data is Digital Elevation Model (DEM) which is the most versatile and useful representation of terrain in GIS. This is a raster representation, in which each grid cell had the elevation of the Earth's surface and used to derive a wealth of information about the morphology of a land surface. Morphology information can be obtained contour lines, point data with elevation values or point cloud data is derived from Light Detection and Ranging (LiDAR) . Slope process is used to indicate the magnitude of steepest tilt of the terrain and the direction of steepest tilt defines the aspect process. The slope can be measured as an angle, varying from 0 to 90 degrees as the surface ranges from horizontal to vertical (Longley et al., 2005) Aspect can be measured from north, it is usually expressed clockwise from 0 to 360 degrees.

2.2.3 GIS as a spatial decision support system

The Multi-criteria decision making methods (MCDM) are a procedure that makes choosing the most appropriate alternatives possible, based on multiple criteria and conflicting objectives, from the feasible alternatives (Sánchez-Lozano et al., 2013).

Geographic Information System is a tool to solve the complicated decision-making problems with MCDM methods which providing a systematic tool for decision makers in selecting the best alternatives between different options (Aydin et al., 2013). The implementation of the MCDM methodology through GIS makes it a significant tool as the Decision-Support System (DSS) for the use of spatial decision making processes such as site selection, resource management and etc. The weighted overlay analysis is one of the MCDM purposes. In the analysis, the input layer with different scores according to their influence is combined with a percentage weight in a single layer. The sum of the total percentage of influencing weight values of all the layers in the weighted overlay analysis must be equal to 100 %. The weight of multiple layers is scaled based on relative importance (Kaliraj et al., 2015)

2.2.4 Use of GIS on solar energy management

Several types of research and application studies have been conducted for the management of the Renewable Energy Source (RES) sources using Geographic Information System (GIS) technology in order to plan the investments put into RES field by accurately selecting the investment sites and applying feasibility studies. Sanchez-Lozano et al. (2013) used a combination of GIS and Multi-criteria decision making (MCDM) methods to find the optimal placement of photovoltaic (PV) solar power plants in southeast Spain. A data set including the location-based environmental (soil maps covering soil types), geomorphological (topography, slope, and orientation) and climatic (solar irradiation potential and average temperature) data is used to select the optimal location of the PV generation plants. Distances to road, power lines and settlements are determined by the use of proximity analysis in GIS.

One of the significant GIS-based solar energy applications is SUN-AREA research project implemented in Osnabrück, Germany (Ludwig et al. 2008, Ludwig et al. 2009). SUN-AREA is a computer-aided analysis method to identify high potential areas for the use of solar power by using GIS. The point cloud data provided by LiDAR technology and plan view data was used in the project for characterizing the rooftops in the urban areas. The method is based on the ArcGIS ModelBuilder from ESRI which gives the user an interface to implement necessary data and tools to model solar power. The result of the project outlined that 70% of the energy demand of Osnabrück can be

covered by only using solar energy with PV installations on the roofs in the city (ESRI, 2010).

The similar methodology applied in SUN-AREA project proposed by Boz et al. (2015) as an automated model for rooftop PV systems assessment. The proposed methodology using Light Detection and Ranging (LiDAR) data and GIS technology together was implemented by the use of Python programming language as an ArcGIS model in ModelBuilder. In the city of Philadelphia in PA, U.S.A, 150 rooftops were analyzed, and 48.6% rooftop areas were assigned as suitable for the establishment of PV systems.

The other outstanding project was completed in the city of Seoul on the assessment of solar potentials of the urban areas. The project used GIS technology and introduced the potential to transform a megacity, which has nearly one-quarter of South Korea's population, into a solar city (Byrne et al., 2015). The complete census methodology, which calculates through existing statistical data sets that contain building-based information such as floor area, the number of floors, and the total number of buildings (Schallenberg-Rodriguez, 2013). The results of the project proved that a potential technical equivalent to almost 30% of the city's annual electricity consumption could be supplied by widespread deployment of rooftop-based distributed photovoltaic systems.

Hofierk and Kanuk (2009) presented a methodology of a PV potential in urban areas with an open-source solar radiation tool called r.sun. The results outlined that 8.1% of urban areas can be directly used to produce electricity in eastern Slovakia. That is equal to approximately 59% of the annual electricity consumption of Slovakia.

At the national level, a site selection research is performed by Uyan (2013) in Turkey for solar farm site selection using GIS in Karapınar region, Konya. AHP methodology is applied GIS application for MCDM of solar farms' locations. Economic factors such as distance from transmission lines and roads, slope and environmental factors such as distance from residential areas and land use were taken into consideration. As a result of which, the study area was categorized into four classes regarding their suitability for the establishment of solar farms.

3. METHODOLOGY

Photovoltaics (PV) transfer the energy of solar radiation into electric current (Voegtle et. al., 2005). Some restrictions have been taken into consideration in order to use this technology efficiently. First and foremost, the implementation should have enough available space, a specific azimuthal orientation, and an efficient slope. In addition to these, the application area should not be exposed to a shadow effect that would cut off the sun's radiation which is caused by surrounding vegetation or buildings. Geographic Information System (GIS) based methodology is designed to calculate the planning purposes and estimation of financial support of rooftop PV applications.

3.1 Use of GIS for Site Selection of Rooftop PV Applications

Usable area for photovoltaic (PV) installations is limited by environmental components, which are caused to set bounds to the attainment of full solar radiation. Therefore, before the implantation of a PV application on the rooftop, appraising the feasibility of system is important.

Urban area for PV applications has complex environmental patterns. Environmental impacts of cities are due to shadows, vegetation, other man-made structural elements, the different angle of surfaces or the lack of available area lead to finding new methods to achieve the effective range of electricity productions by PV panels. Geographic Information System (GIS) is a tool to let users find the suitable location of rooftop PV applications in complex environmental patterns.

The fundamental requirements of the applied methodology are rooftop extraction, slope and aspect analysis. The flow chart of the methodology is presented in Figure 3.1. The data source that will form the basis to obtain fundamental inputs can be obtained in two ways. Remote sensing technology and photogrammetry can be used to obtain the 3D point cloud data. Light Detection and Ranging (LiDAR) that stores the geometrical information of a scanned surface as a 3D point cloud, with

photogrammetry, pairs of geo-referenced photographic images allow creating a 3D model of the surface (Freitas et al., 2015).

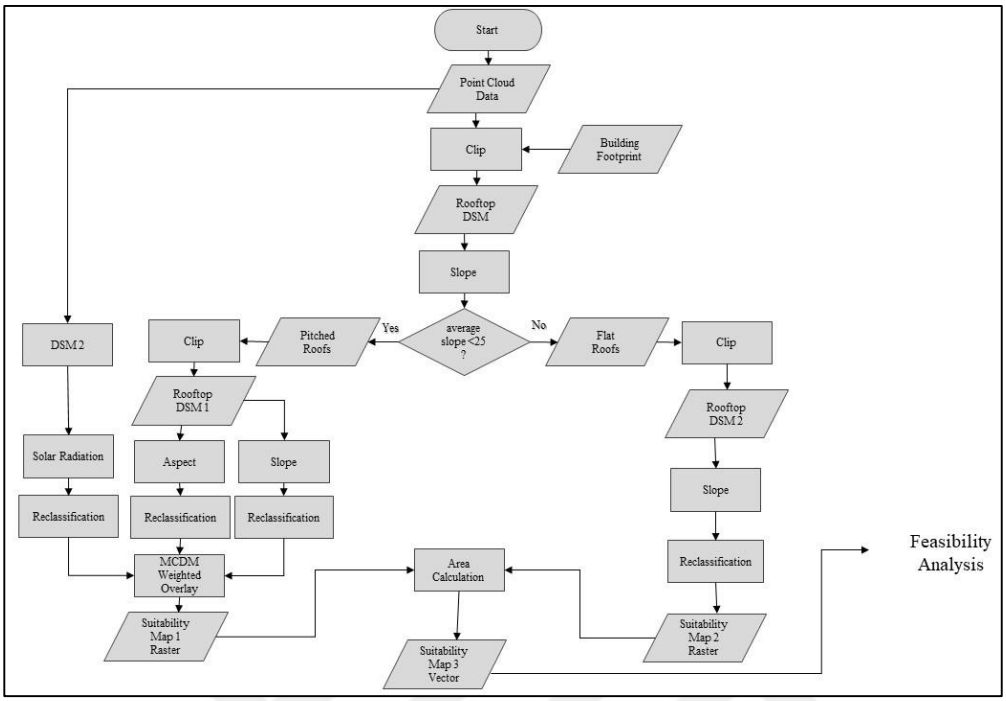

Figure 3.1 : Flow chart of suitability analysis.

Characterization of the rooftop geometry is necessary for the rooftop PV site selection process. The type of rooftops is selected attribute data of the building footprint. Flat and pitch roofs are required independent analyses of each other. If a roof is considered pitched, slope and aspect analysis are required for calculating available areas, on the other hand with the flat roofs; slope analysis is enough for calculating available areas. Both types of roofs were analyzed without shading factor caused by surrounding features. All of the output data is put together to analyze with decision support system methods.

3.1.1 Solar radiation

Solar radiation data is available in several forms. The solar radiation intensity receiving to a surface is called irradiance or insolation, and it is measured in W/m^2 or kW/m^2. Irradiance is the amount of solar energy incident per unit area per unit time and the most suitable criteria in the assessment of the solar resource at a geographical location (World Energy Council, 2016). Components of solar radiation are direct and diffuse radiation. Diffuse Radiation means “the solar radiation received from the sun after its direction has been changed by scattering by the atmosphere.” (Duffie and Beckman, 2013). The sum of the beam and the diffuse solar radiation is total solar

radiation or global radiation at the Earth's surface. Direct beam radiation reaches the surface of without any interactions with particles in the atmosphere (Figure3.2). For different types of applications, solar radiation data is given as Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI). The total amount of solar energy incident to a horizontal surface is defined as GHI and DNI is the amount of radiation incident on a surface that is perpendicular to the direct solar beam (World Energy Council ,2016). Coupling solar radiation with Geographic Information System (GIS) is improved accuracy of radiation calculations.

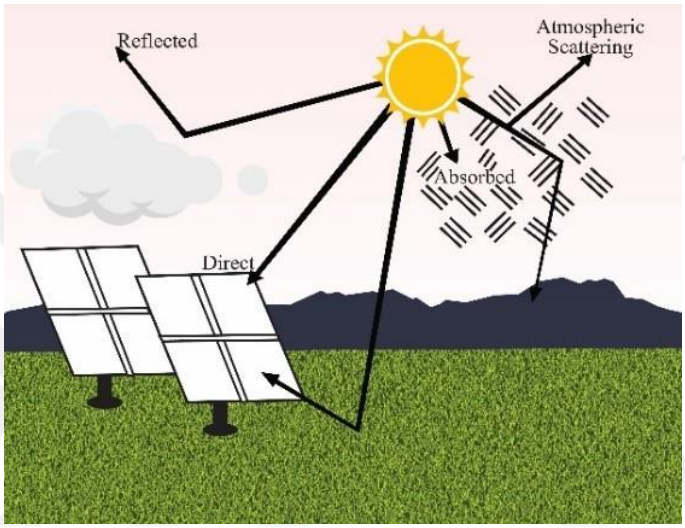

Figure 3.2 : The components of incoming solar radiation adapted from (World Energy Council, 2016).

Open-source technologies are an option to calculate solar radiation. GRASS GIS is an open-source GIS software and provides a model called as r.sun. Conceptually the model based on European Solar Radiation Atlas. The model calculates beam, diffuse and reflected solar radiance for clear skies (Suri and Hofierka, 2004).

ESRI defines the solar radiation analysis tool as a method based on the hemispherical view shed algorithm developed by Fu and Rich (2000, 2002). Tool accounts for "atmospheric effects, site latitude and elevation, steepness (slope) and compass direction (aspect), daily and seasonal shifts of the sun angle, and effects of shadows cast by surrounding topography" (Url-2).

Solar radiation analysis tool can calculate for a particular location or selected area. Generally, model inputs are the location (latitude), elevation, orientation and atmospheric transmission (Freitas et al., 2015).

The calculation of direct, diffuse, and global insolation is for each feature location or every location on the surface, producing insolation maps for an entire geographic area (Url-2).

Area solar radiation (ASR) tool of ArcGIS software is selected to calculate the GHI as an input for solar radiation data, and the fundamental equation which is the background of ASR is considered below (Url-2).

The sum of direct (Dir_{tot}) and diffuse (Dif_{tot}) radiation of all sun map and sky map sectors are Global radiation ($Global_{tot}$)

$$Global_{tot} = Dir_{tot} + Dif_{tot} \quad (1)$$

The sum of the direct insolation ($Di_{r\theta,\alpha}$) from all sun map sectors give results as Direct solar radiation (Dir_{tot}) for a given location is;

$$Dir_{tot} = \Sigma\, Dir_{\theta,\alpha} \quad (2)$$

The equation below is to calculate the direct insolation from the sun map sector ($Dir_{\theta,\alpha}$) with a centroid at zenith angle (θ) and azimuth angle (α)

$$Dir\theta,\alpha = S_{Const} * \beta^{m(\theta)} * SunDur_{\theta,\alpha} * SunGap_{\theta,\alpha} * \cos(AngIn_{\theta,\alpha}) \quad (3)$$

where:

S_{Const} – solar constant is the solar flux outside the atmosphere at the mean earth-sun distance. The solar constant used in the analysis is 1367 W/m^2 (World Radiation Center (WRC))

β – The transmissivity of the atmosphere for the shortest path. Averaged over all wavelengths and in the direction of zenith.

$m(\theta)$ – Measured as a proportion relative to the zenith path length is the relative optical path length

$SunDur_{\theta,\alpha}$ – The time duration represented by the sky sector.

$SunGap_{\theta,\alpha}$ – The gap fraction for the sun map sector.

$AngIn_{\theta,\alpha}$ – The angle of incidence represented between the centroid of the sky sector and the axis normal to the surface.

Relative optical length, m(θ), is calculated with the solar zenith angle and elevation above sea level. For, the following equation is for the calculation of zenith angles less than 80°.

$$m(\theta) = EXP(-0.000118 * Elev - 1.638*10^{-9} * Elev^2) / \cos(\theta) \quad (4)$$

where:

θ – The solar zenith angle.

Elev – The elevation above sea level in meters.

The effect of surface direction is used with by multiplying by the cosine of the angle of incidence. The angle of incidence ($AngInSky_{\theta,\alpha}$) is between the intersecting surface and a given sky sector with a centroid at zenith angle and azimuth angle which is calculated using the following equation:

$$AngIn_{\theta,\alpha} = acos(Cos(\theta) * Cos(G_z) + Sin(\theta) * Sin(G_z) * Cos(\alpha-G_a)) \quad (5)$$

where:

G_z – Zenith angle of the surface.

G_a – Azimuth angle of the surface.

The diffuse (Dif) radiation at its centroid, for each sky sector, is calculated, integrated over the time interval. The correction is done by the gap fraction and angle of incidence with the following equation.

$$Dif_{\theta,\alpha} = R_{glb} * P_{dif} * Dur * SkyGap_{\theta,\alpha} * Weight_{\theta,\alpha} * \cos(AngIn_{\theta,\alpha}) \quad (6)$$

where:

R_{glb} — The global normal radiation

P_{dif} — The proportion of diffuse global regular radiation flux. Commonly it is approximately 0.2 for very clear sky conditions and 0.7 for very cloudy sky conditions.

Dur — The time interval for analysis.

$SkyGap_{\theta,\alpha}$ — The gap fraction (proportion of visible sky) for the sky sector.

$Weight_{\theta,\alpha}$ — The proportion of diffuse radiation originating in a given sky sector relative to all sectors

AngInθ,α — The surface angle of incidence is an angle between the centroid of the sky sector and the intercepting.

The global normal radiation (R_{glb}) can be calculated with an addition summing the direct radiation from every sector (including obstructed sectors) without correction for the angle of incidence, later on correcting for the proportion of direct radiation, which equals 1-P_{dif}:

$$R_{glb} = (S_{Const} \Sigma(\beta^{m(\theta)})) / (1 - P_{dif}) \quad (7)$$

The output radiation raster will always be the floating-point type, and the unit of output will be units of watt-hours per square meter (Wh/m^2). The direct duration raster output will be an integer with unit hours.

3.1.2 Rooftop extraction

Three-dimensional (3D) models are the primary data for the rooftop detection. 3D point cloud data can be provided by photogrammetric techniques or light detection and ranging (LiDAR) sensors. LiDAR is a remote sensing technology, based on active sensors, to characterize surfaces with high precision (Lukac et al., 2014). In the context of a project done on campus, 3D point cloud was obtained with air photogrammetry and this source of this data was used in study. According to the building rooftop outline data digitized from orthophotos or building footprint, rooftop extraction can be clipped from the point cloud. Building footprints represent the outline of a building, and generally, they are compatible with the outline of its roof. The building outline is an easy method to determine the roof area that is exposed to the sun. If the building footprint data is to be used, a buffer distance should be calculated taking into account the surrounding factors for an accurate calculation (Kodysh et al., 2013). If the roof outline data is obtained from orthophoto, buffer distance can be ignored. Then, clipping process is performed with a 1m buffer distance of footprint vector data, or extract rooftop polygon can be used without any buffer to select the rooftops. The obtained data is used for slope and aspect process.

3.1.3 Orientation

The power contained in the sunlight and the angle between the module and the sun are important points for the energy collection of solar photovoltaic (PV) panels hence, the optimum tilt angle (ßopt) plays an important role. In generally, rooftop PV systems are

fixed-tilled that means they do not track the path of the sun. In the northern hemisphere, the optimum orientation is south facing. The south-facing slopes receive the best sun expose (MacDonald, 2014). Gunerman and Hepbasli (2007) are made a study for İzmir. The results of the study showed that; the optimum tilt angle changes according to the latitude and the days of a year. If the system will be fixed-tilled and utilize solar energy throughout the year, the optimum tilt angle can be taken to be equal to the latitude(φ) of the location. For different seasons of the year, optimum tilt angle will differ by up to 15° from latitude for in summer is ßopt = φ + 15° and for in winter ßopt = φ – 15° (Gunerman and Hepbasli, 2007). The study mentioned above will be the reference to accept the optimum angle equals to latitude for the application of the methodology. The south-facing roofs and the slope that is equal to the latitude angle will represent the best suitable area to establish PV application. The rank is assigned with this situation.

3.2 Use of GIS for Feasibility Analysis of Rooftop PV Applications

Feasibility analyses include the initial cost, potential savings, annual income and expenses, depreciation (Batman et al., 2012). The recent studies showed that energy depreciation time of commercial photovoltaic (PV) systems under the meteorological and environmental circumstances in the Southern Europe is 0.7 to 2.5 years (IEA, 2014). Additionally, Bhandari outlined the economic lifetime of PV systems as around 30 years (Bhandari et al., 2015).

The suitable area calculations and classifications, which are required for feasibility analysis, are made with Geographic Information System (GIS) analyses. The results obtained from the suitability area calculation are used as input data for the feasibility analysis. The feasibility analysis calculations are shown in Figure 3.3.

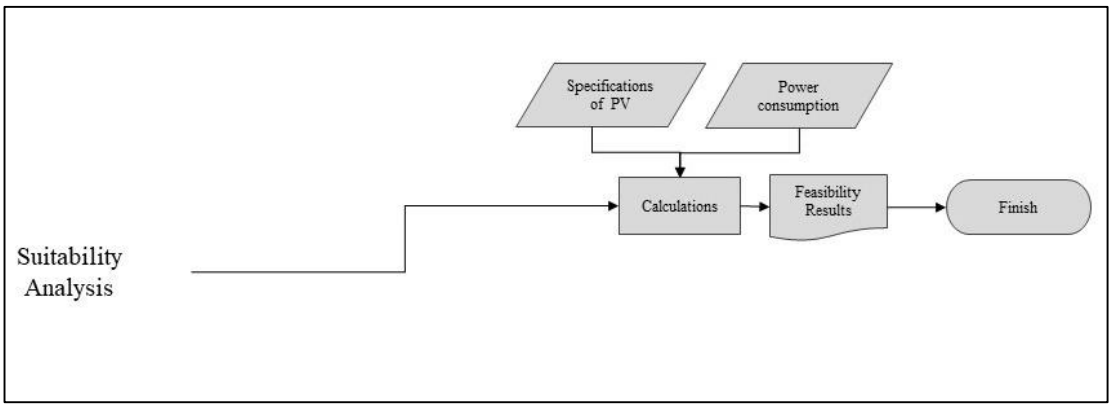

Figure 3.3 : The flow chart of feasibility analysis.

3.2.1 Types of Photovoltaic

Solar photovoltaic (PV) panels are the key to developments in solar energy production. PV cells are a semiconductor material, and they are connected together in series and parallel to obtain a desired operating voltage and current. Mono-crystalline silicon, multi-crystalline silicon, silicon (Si), and thin film technologies, such as cadmium telluride (CdTe) are the materials of commercial PV. The most developed technology is silicon-based cells. Due to the readily availability of silicon, crystalline Si thin films are great interest. Another reason of interest is the high conversion efficiency of Si solar cells which is close to 25% (Yilmaz et al., 2015). Polycrystalline PV panel type, which is a kind of the silicon-based photovoltaics, will be examined for the feasibility analysis. The model of the polycrystalline panel is CWT270-60P 270W. The price offer and technical information are received from the manufacturer of the PV panel. The unit price of the panel CWT270-60P 270W is specified as 143,10 USD. Technical specifications are explained with details in Table 3.1 and 3.2.

Table 3.1 : Mechanical specifications of solar PV panel.

Mechanical Specifications	
Cell Type	156,75mm x 156,75mm
Number of Cells	60 (6X10)
Weight	19.5 kg
Dimension	1648×995×35mm
Max Load	5400 Pascal

Table 3.2 : Electrical specifications of solar PV panel.

Electrical Specifications			
Peak Power (Wp)	270W	Short Circuit Current (Isc)	9.06A
Module Efficiency	16.47%	Power Tolerance	±5%
Maximum Power Voltage (Vmp)	31.2V	Maximum System Voltage	VDC 1000V
Maximum Power Current (Imo)	8.65A	Nominal Operating Cell Temperature	-40 ~ +85°C
Open Circuit Voltage (Voc)	38.6V	Maxiumum Series Fuse Rating)	15A

4. IMPLEMENTATION

4.1 Study Area

The Ayazaga Campus of Istanbul Technical University, Sarıyer district, Istanbul Turkey, is the study area. Specially, the housing area of Istanbul Technical University was chosen as the region for model implementation implementation (Figure 4.1). The different structural kind of roofs was selected as sample rooftop to implement the model. The location maps clarified the implementation area with the location in the province, district, and campus.

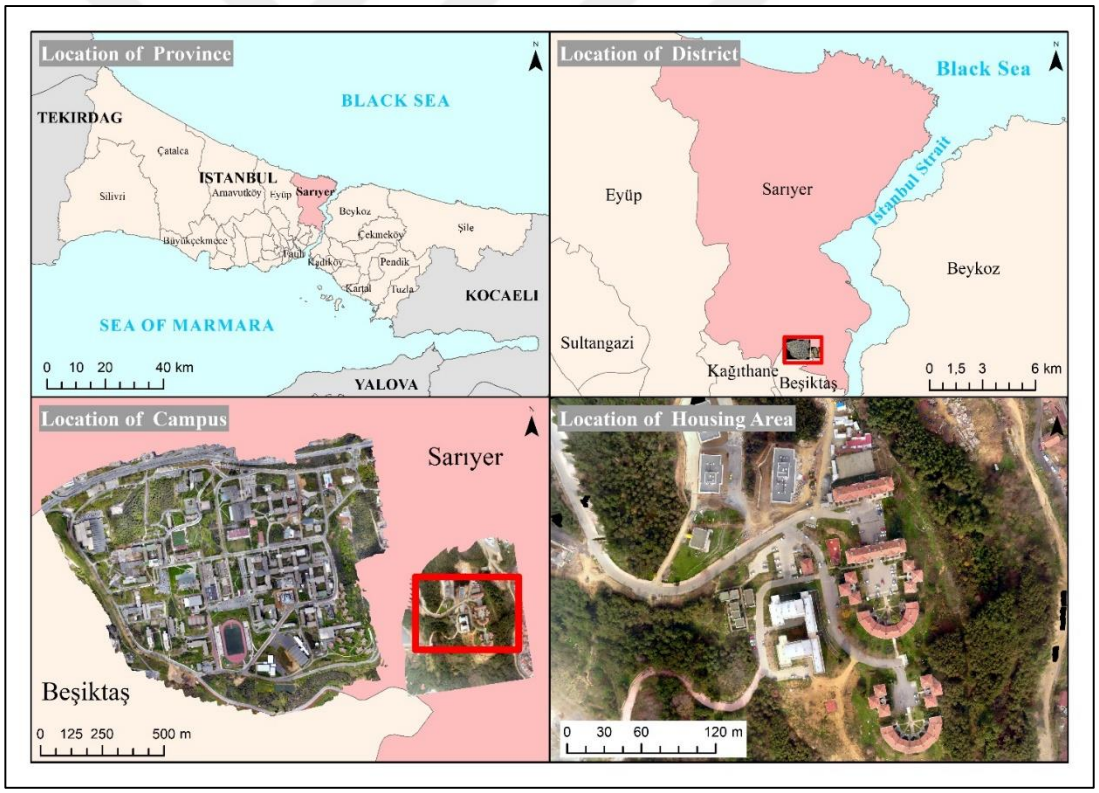

Figure 4.1 : Study area.

4.2 Data

Building rooftop outline and 3D point cloud data were the inputs of the model. Rooftop data was a vector layer in shape file format. The rooftop data was digitized from orthophoto. 3D Point cloud data was provided by the Geomatics Engineering

Department as an output of a Design Project Submission focusing on 3D modelling of ITU Ayazaga Campus. The stated data acquired using Unmanned Aerial Vehicle as an aerial photogrammetry application. 3D point cloud data were converted from ASCII format to feature. Point cloud data enables to derive a digital surface model (DSM). Surface model of rooftops and terrain can be obtained by DSM. The stated data sources were referenced in Transverse Mercator grid zone with central meridian 30 based on the International Terrestrial Frame 1996 datum. All inputs were summarized in Table 4.1.

Table 4.1 : Data specifications.

Name of Dataset	File Format	File Extension	Spatial Formant
Building Rooftop Outline	Shapefile	.shp	Vector
Point Cloud Data	ASCII	.txt	Vector

4.3 Applied Methodology

The methodology estimates the available and effective area of the rooftops for photovoltaic (PV) application. The main parameters affecting the suitability analysis are:

- Rooftop size
- Rooftop slope
- Rooftop aspect
- Incoming solar radiation

The workflow of the model is shown Figure 4.2. The ArcGIS 10.X software is used for all the geo-processing. The ModelBuilder extension allows combining the individual process to create a new tool. ModelBuilder can be defined as a visual programing language which allows creating own tool (Url-3). The ModelBuilder diagram is visualization in Figure 4.4. When the required data added as inputs and the output location identified, the model implements the intermediate steps until it produces the final product. The user interface of the model is shown Figure 4.3.

The analysis is based on digital surface model (DSM) which is obtained from 3D point cloud data. The DSM was used in two ways. In a first way, DSM was specified with clip process to perform analysis only the rooftop area. In the second way, the same DSM data was used without clipping process to calculate the solar radiation.

The pilot area contains two types of roofs (Figure 4.4). Pitched roofs have an average slope greater than 25^0 and flat roofs have less slope degree than 25^0 (Alexander et al., 2009). This classification was calculated with zonal statistic tool. (Figure A.3) The inputs of the tool were the slope of the rooftops and building rooftop polygons. The mean statistic was implemented, and then the selection was made after the reclassification process was applied one by one the outputs of the pitched and flat rooftops.

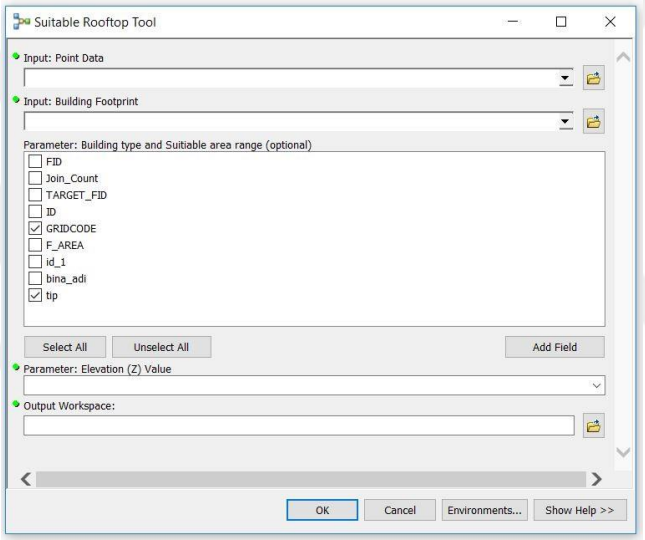

Figure 4.2 : The interface of model.

Figure 4.3 : The rooftop classification of the pilot area.

The analysis proceeded from two separate ways and calculated two separate suitability for two different roof types. While analysis of the aspect, slope and solar radiation was required for the pitched roofs, only slope analysis was performed for the flat roof. The reason of the differences are the cost of installations. It is anticipated that extra cost will be required to provide proper slope and aspect on flat roofs.

The results of spatial analyses were reclassified. The reclassification values assigned relative importance of each factor. The classification range is between 1-4. The higher weight value was assigned as 4 with maximum potential magnitude. 1 value was assigned as inapplicable area, and it was not considered in weighted overlay process. The remaining values were assigned according to the effects of the factors. Then, the weighted overlay process was performed by accepting the resultant effects at different percent. The sum of the total percentage of the weight of all parameters must be equal 100% in the weighted overlay process. The reclassification outputs of slope, aspect and solar radiation were used as inputs of weighted overlay process. The influence percent was selected 20%, 60% and 20%, respectively. The overlay analysis result was converted from raster to feature, and spatial join process was done to attend the building ID. Building ID is necessary to combine the segments which are the same roof and the same suitability value. After the process, the area of rooftops is less than 2 m^2 are eliminated because of the panel area. The average area covered by a panel is 2 m^2. The final implementation area for PV panels is calculated to use in feasibility analyses.

The main purpose of the feasibility analysis is to establish the relationship between the available space and the energy to be produced. By determining the number of panels to be placed at the suitable areas, profit and loss balance can be established by calculating panel cost and electricity generation. Assuming that the system is on-gird, the amount of consumption can be compensated and accordingly the system's self-depreciation time is calculated. Only the cost of the panel was calculated as the cost and Wp value of the PV panel was used the calculation of the electricity generation.

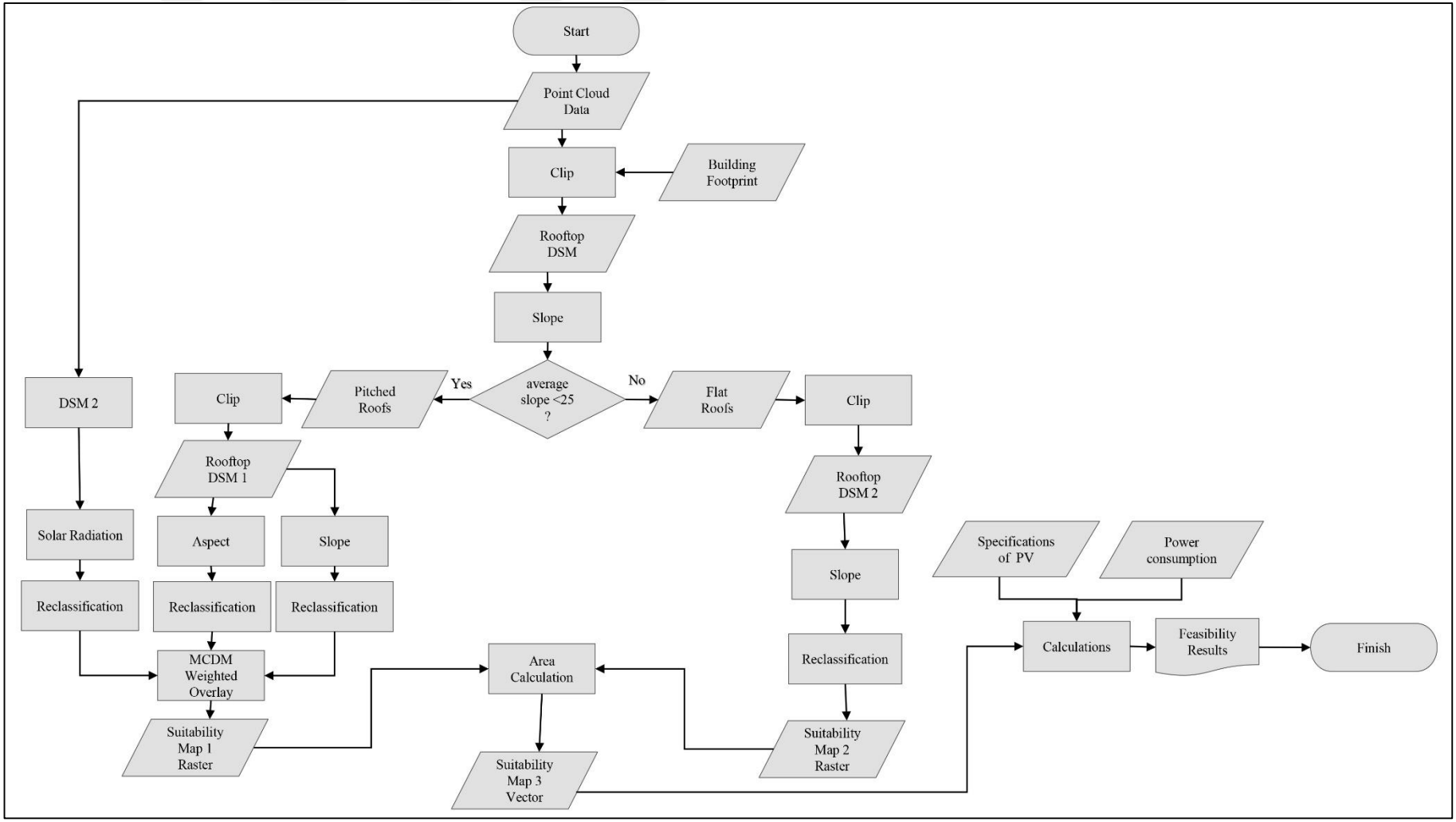

Figure 4.4 : Flow chart of the model.

5. RESULTS

5.1 Suitability Analysis

When the suitability analysis was implemented, the Geographic Information System (GIS)-based multi-criteria decision making (MCDM) process was used to solve decision problems and evaluate the alternatives. One of the MCDM, the weighted overlay analysis was implemented. Architectural and environmental factors were integrated to identify the location selection using raster weighted overlay analysis. Slope, Aspect and Solar Radiation Analysis are the principal factors of the finding suitable location for the rooftop photovoltaic application. Thirteen buildings were calculated. The analysis output was reclassified into four classes (Figure5.1).

When the first three classes show the suitability with the rating, the last class shows the areas where the installation cannot be done. The reason for the unsuitable locations is based on high slope values. The whole model diagram was shown in Figure A.1. The description of each step will be made the next titles.

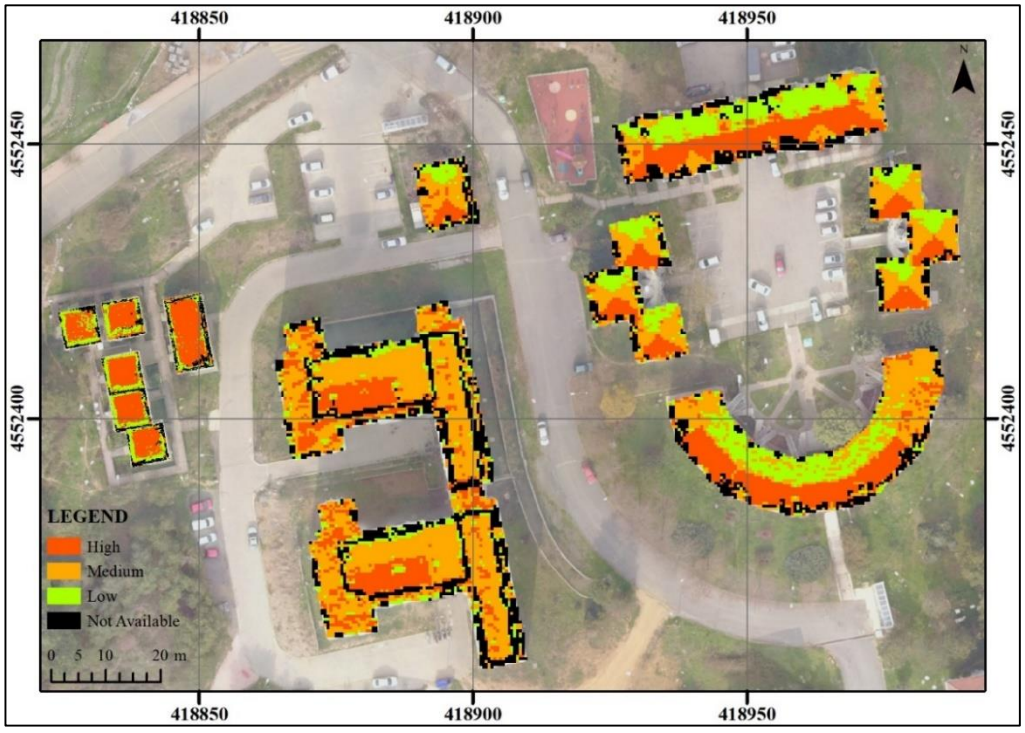

Figure 5.1 : Raster format of results of the model.

Another significant result to be obtained by classifying the roofs according to their suitability is to find the answer to the how much space covers each group. For area calculation, the raster data converted to vector data format. As a PV panel had an average coverage of $2m^2$, smaller pieces of the area than $2m^2$ were extracted (Figure5.2). By joining building ID, the areas were calculated for each building with suitability rating. The area calculation results were shown in Table 5.1. These calculations will be evaluated for energy production calculations in the feasibility analysis section.

Table 5.1 : Suitable area calculation results.

Rating	Building ID	Area (m^2)	Rating	Building ID	Area (m^2)
Pitched Roof			Flat Roof		
High	1	182	High	8	56
Medium		182	Low		3
Low		132	Not Available		16
Not Available		60	High	9	23
High	2	53	Low		10
Medium		91	Not Available		None
Low		51	High	10	22
Not Available		27	Low		10
High	3	56	Not Available		3
Medium		105	High	11	75
Low		52	Low		34
Not Available		19	Not Available		12
High	4	170			
Medium		82			
Low		156			
Not Available		87			
High	5	105			
Medium		330			
Low		7			
Not Available		147			
High	6	96			
Medium		345			
Low		8			
Not Available		129			
High	7	16			
Medium		45			
Low		15			
Not Available		19			

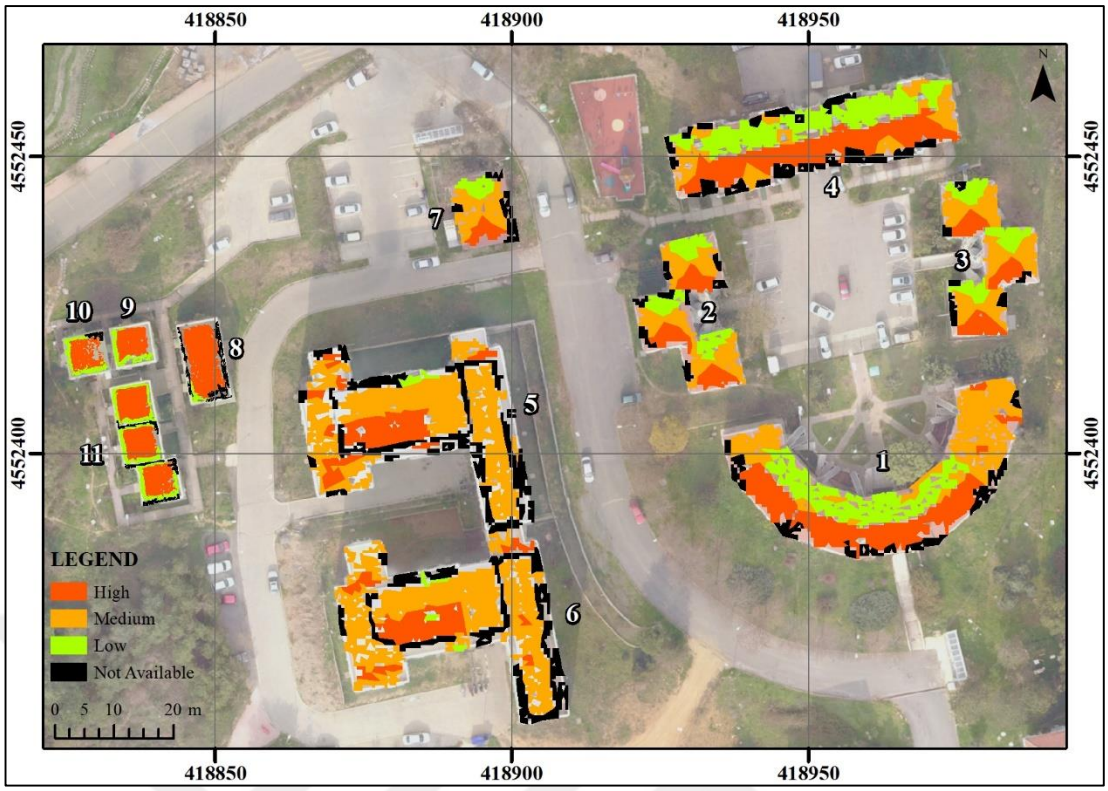

Figure 5.2 : Vector result map with area calculation.

5.2 Slope analysis

The slope is the inclination of the surface. In the model, the slope analysis was done after the clipping process of 3D point clouds and the conversion process of the feature to raster (Figure A.3)

The clipping process was done for flat and pitched roofs, separately. The slope was calculated with the extracted rooftop of the digital surface model. The most suitable rooftop angle equals latitude of the application area (Gunerman and Hepbasli, 2007). The latitude of the study area is 41 degrees. The 0-15 degree is accepted as plain and high usable regions of pitched roofs. The most suitable degree is accepted between 30-45, because of the latitude degree for the pitched roofs. For flat roofs, slope analysis was performed to find the precise available area on the roof due to eliminate the structural components. Between 0-15 degree was accepted suitable. Values higher than 60 degrees were considered unsuitable for flat and pitched roofs (Alexander et al., 2009). The new values were assigned from high suitability to low suitability, from 4 to 1, respectively.

Table 5.2 : The assigned values of slope

Slope Degree	Assigned Value	Slope Degree	Assigned Value
Pitched Roof		Flat Roof	
0-15	4	0-15	4
15-30	3	15-60	2
30-45	4	60-90	1
45-60	2		
60-90	1		

Which region of rooftops have which slope suitability class can be seen in slope analysis map that is one of the model's moderate outputs (Figure 5.4). If the slope analysis is examined closely before the reclassification, it is likely that the 5 and 6 rooftops are very close to being taken to the flat roof class. However, they were taken to the pitched roof class because their average slopes were below the threshold.

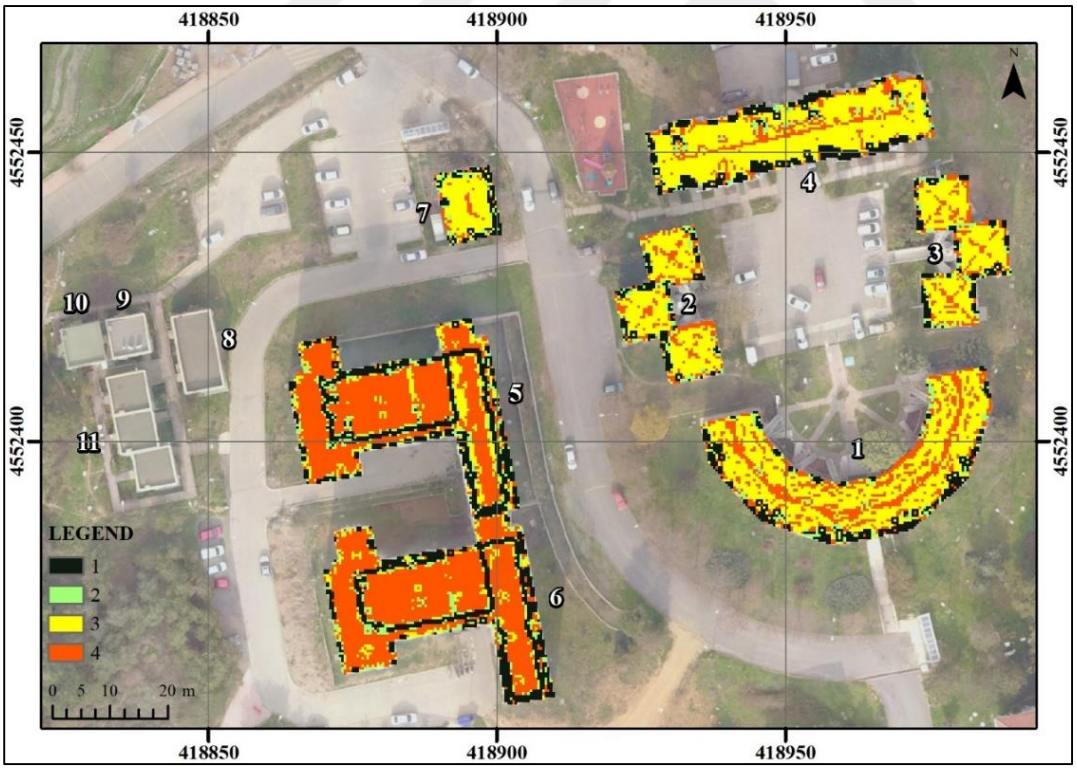

Figure 5.3 : The results of slope reclassification for pitched rooftops.

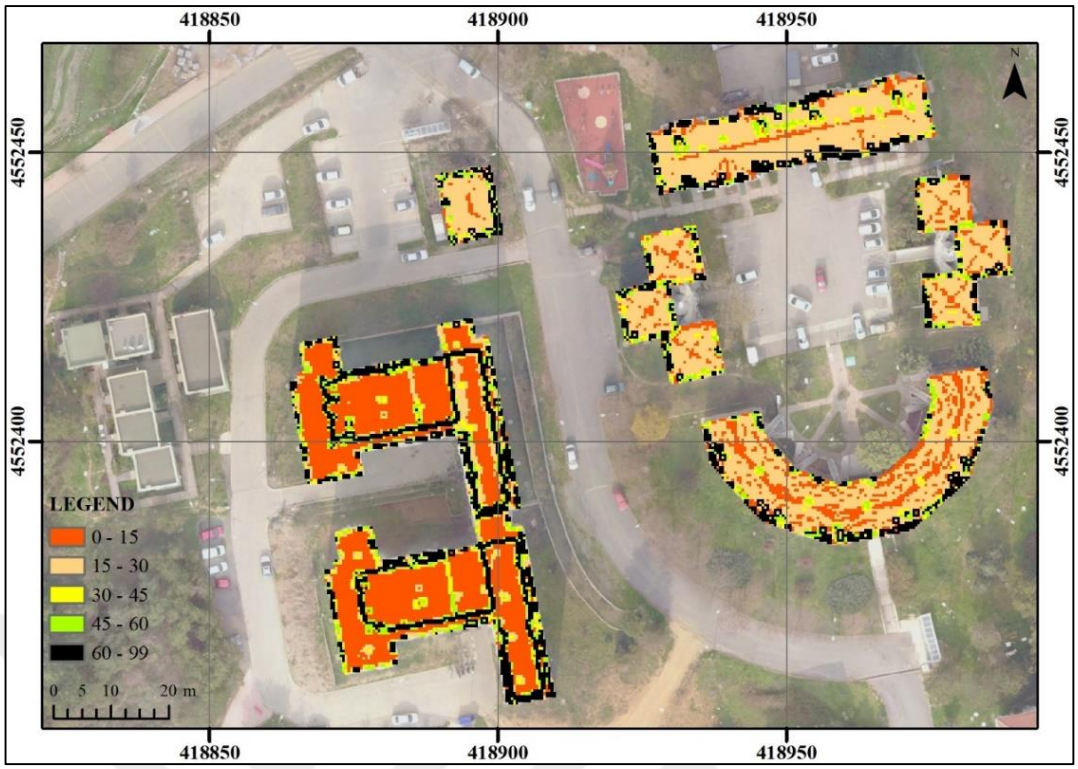

Figure 5.4 : The results of slope analysis for pitched rooftops.

5.2.1 Aspect analysis

Aspect refers the slope direction. The result of analyses, reclassification was implemented according to the table 5.3. N, NE, NW are less suitable directions, E and W directions are medium and S, SE, SW are the most suitable directions (Bayrakci Boz et al., 2015). This analysis was implemented only in pitched roof since flat roofs have not any value of aspect. The aspect analysis inputs are the same with slope analysis. In the decision-making process, the percent of aspect was taken higher than the other factors in the weighted overlays process. The slope of the panel can be changed with extra cost, but the aspect of the building will be stable.

Table 5.3 : The assigned values of aspect

Slope Direction	Assigned Values
Pitched Roof	
N	2
NE	2
E	3
SE	4
S	4
SW	4
W	3
NW	2
N	2

According to rooftops orientation, the classified aspect map is shown in Figure 5.6. When compared with the final suitability map, the effect of the aspect analysis can be seen due to the high percentage of weighted overlap process.

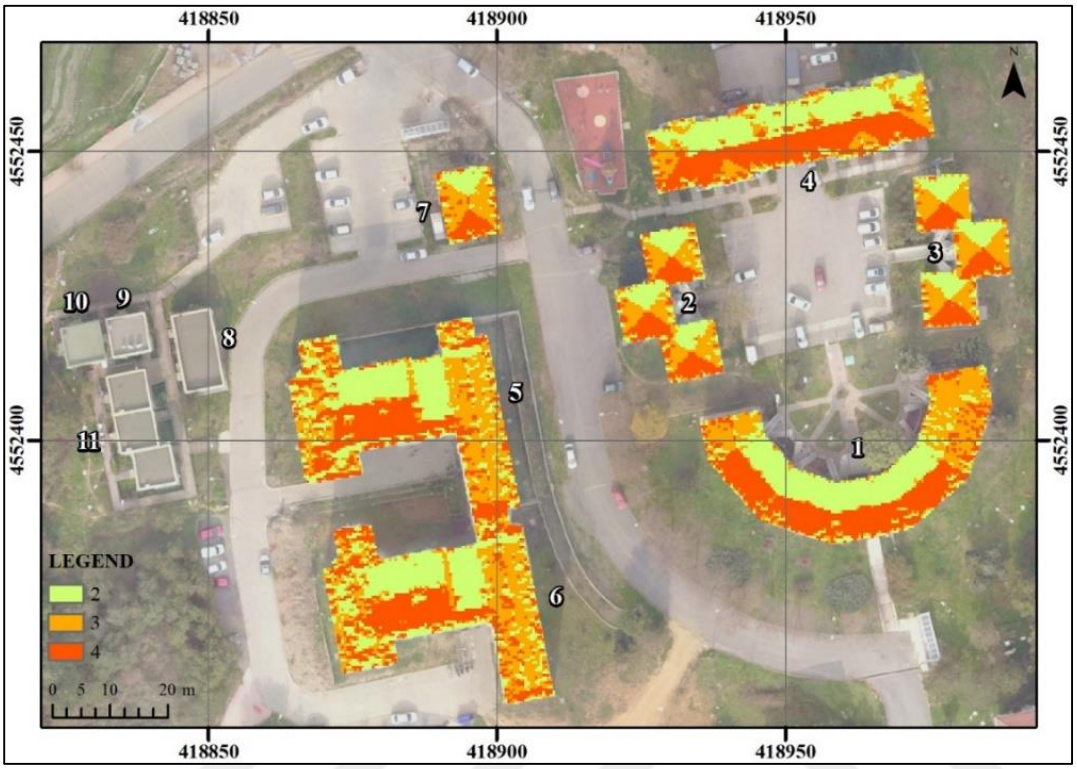

Figure 5.5 : The results of aspect reclassification for pitched rooftops.

5.2.2 Solar radiation analysis

Solar radiation was calculated with Area Solar Radiation (ASR) took which is the tool of ArcGIS. Time configuration was selected “Whole year with a monthly interval.” The hour interval was selected 0.5 hours. In addition, the standard parameter was chosen to derived slope and aspect which the ASR tool required. The global solar radiation was calculated. Solar radiation data was used to classify regions where the radiation is high. It is not taken into account in the electricity generation. Tablo 5.4 shows the solar radiation values and the newly assigned values. The point cloud data was used to a derived digital surface model which was used as an input in the model . Solar radiation analysis performed all the area (Figure 5.7), but it was only used for pitched rooftops because the ASR tool includes as a fundamental process slope and aspect analysis.

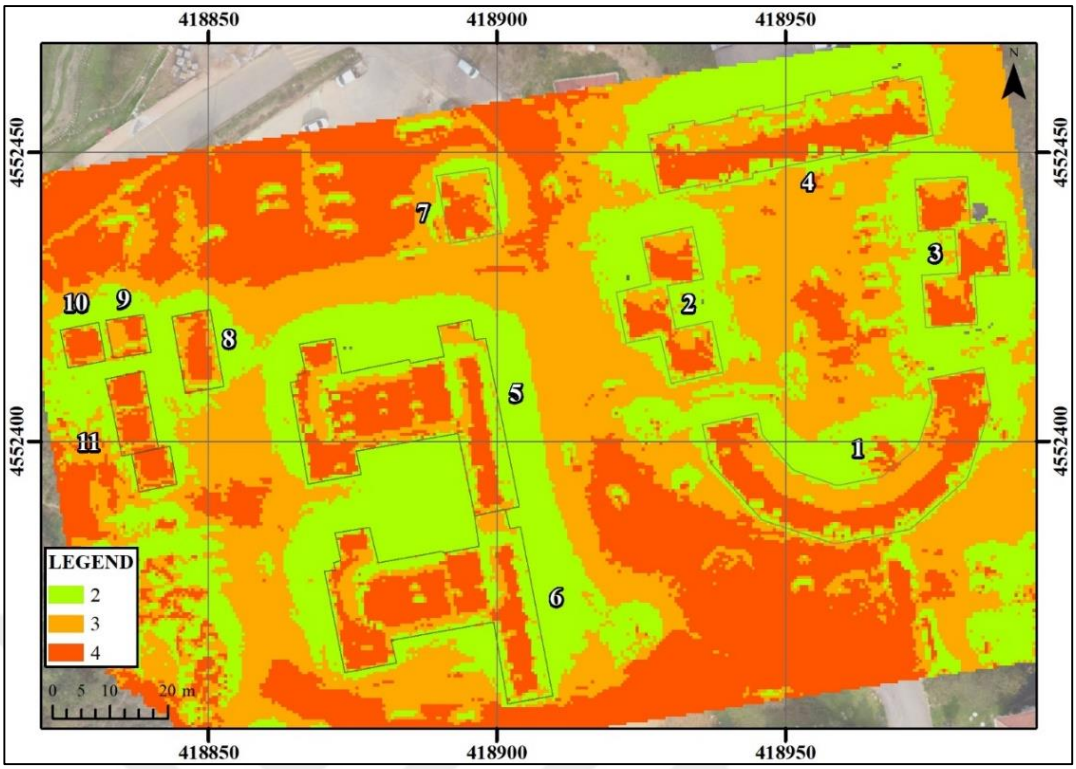

Figure 5.6 : The results of solar radiation reclassification.

In this study, the plain areas were selected on the flat roof to find the The results of solar radiation reclassification installation regions of the photovoltaic (PV) with an aspect and slope different from the rooftop structures. The calculation of slope and aspect of the installed PV will not be taken into the analysis.

Table 5.4 : The assigned values of solar radiation.

Solar Radiation (kWh/m^2)	Assigned Values
1-250	2
250-500	2
500-800	3
800-1100	3
1100-9999	4

5.3 Feasibility Analysis

Photovoltaic (PV) power plants can be mounted fixed angle facing the Equator or two axes solar tracking device to follow the sun position. The system includes power condition appliances, mainly inverters which convert the DC generated by PV into AC suitable to be fed into the grid and batteries (Martín-Chivelet, 2016).

CWT270-60P 270W polycrystalline panel was used to estimate feasibility. The peak power of the system is the nominal power of every module. Nominal power is rated at

standard test conditions are 1 kW/m^2 solar irradiance, 1.5 air mass, cell temperature of 25^0C. Module efficiency, size and number effect the peak power of PV system. The PV module's efficiency is the ratio of power density supplied by the module to the solar irradiance it receives. Peak power and nominal power severalize with a symbol a, p or AC subscript, as kWp or kWAC. Technological developments of the module are necessary to obtain higher efficiency at the relatively small spaces (Martín-Chivelet, 2016).

The peak power of the panel was taken consideration, so the high-value regions of the roofs were put in practice. The area covered by one module is average 2m^2. Therefore, Areas under 2 m^2 were extracted from the suitability map. After this, the suitable areas of the rooftops were determined and decided to the number of panels. The number of panels to be installed was decided only for pitched roofs. The analyses were carried out considering the architectural structure of the roof for PV installation without adding any additional constructional elements. For flat roofs, only suitable plain areas were estimated. The calculated area is not suitable for feasibility analysis because the installation area will change due to the slopes and the views of the panels to be installed.

The cost of the CWT270-60P 270W was required from the production company. The average price of a single module was given 143.1$.

The average sunshine duration of Sarıyer was taken from the Solar Energy Potential Atlas (GEPA) (Url-7). The sunshine values were shown in Table 5.5. The average sunshine duration was used to calculate daily electricity production.

The module counts, available area, energy production values are shown in Table 5.6. The production of the electricity depends on panel module count. The other components of PV system, inventers, support equipment, cables, were not taken into account. So the cost can be considered as minimum installation cost. The cost of panel changes the purchase amount of panels, production density and transportations type.

Table 5.5 : Sunshine duration of Sariyer Istanbul (Url-7).

Month	Sunshine Duration (h)
January	3.39
February	4.26
March	5.20
April	6.57
May	8.31
June	10.19
July	10.72
August	9.71
September	7.86
October	5.05
November	3.78
December	2.99
Average	6.50

Table 5.6 : The feasibility results of highly suitable areas.

Building ID	Area (m^2)	Number of Panels	kWh	kWh/day	kWh/month	Panel Cost($)
1	182	91	25	160	4791	13022
2	53	26	7	46	1369	3721
3	56	27	7	47	1422	3864
4	170	84	23	147	4423	12020
5	105	52	14	91	2738	7441
6	96	48	13	84	2527	6869
7	16	7	2	12	369	1002
Total	678	335	90	588	17638	47939

The electricity consumption of building 5 was used at the detailed feasibility calculations. Building 5 has 65 apartments. The electricity consumption in July 2016 was 3208 kWh. As seen in Table 5.5, the sunshine duration in July is 10,72 h. If the calculation was made according to the sunshine of July, the monthly electricity generation related to the installed capacity would be 4515 kWh. However, it should not be forgotten that the panels can not work with 100% efficiency, that the production changes according to the incoming solar radiation and those energy losses due to the transmission are experienced. Even if it is thought that the production of these losses is around the 50%, it is possible to cover the 70% of the electricity consumption of the building 5 from the roof PV panel systems.

When the calculations of buildings according to the yearly average electricity consumption of the building number 5 are made, the annual electricity consumption is 46 116 kWh and the invoice amount paid is 12 420 TL approximately 3 253 dollars. It

is estimated that the annual electricity generation of the installation at most suitable locations, which is supposed to be built at building number 5, is 32 853 kW/h. When averages are taken on a monthly basis, the electricity consumption is 3843 kWh, the paid amount is 1035 TL, about 271 $. It is seen that the production produces more than the annual value, and if it is considered that the system sells electricity depending on the network, on-grid PV system, electricity sales of 13 260 kWh per year can procurable. The distinction between consumption and production is equivalent to about 4 months of electricity consumption, it can be considered that 4 bills and the income per year earned will be 4 140 TL, about $ 1 084. Only the cost of purchasing the panel is $ 7 441, and the period of depreciation time can be calculated as 28 months. Calculations was calculated as profit on invoice and costs might be changed depending on the on-grid or off-grid installations. It should be remembered that, costs that will arise outside of the panel cost as, inventor, installation, transportation, official permission, maintenance, and in the necessary cases the storage costs were not into taken consideration.

6. CONCLUSIONS AND DISCUSSIONS

This study aims to increase the usage of renewable energy in the spare region of the urban. The method extracts the suitable rooftops based on slope and aspect analyses. While this analysis, the point cloud data was the primary input. ArcGIS 10.2 was used to implement GIS operations and the combining all the analyses tools in one model. ModelBuilder with python programming background made the all steps one user-friendly interface. The implementation area was the Istanbul Technical University, Ayazaga Campus. In the pilot area, 11 buildings were analyzed, and 7 of them was pitched roof, 4 of them was a flat roof. In the panel setup, it was accepted that the installation process would be done without changing the orientation. So,the feasibility studies were carried out on the pitched roofs. Ludwig et al., (2009) is mentioned, the roof size should be at least 15m^2 to be suitable due to economic reasons and according to Bayrakci Boz et al., (2015) the minimum area of rooftop depends on the total roof area commonly acceptable area is 10 m^2. However, when examined the panel dimensions, it is seen that the single bridging module occupies about 2 m^2. Unlike the studies mentioned above, areas larger than 2 m^2 were included in the calculation. In order to see the results from the usage of even one PV panel module, the area calculation was preferred different from the common acceptance. The total available area is 678 m^2, and the total panel module count is 335. If the daily sunshine duration was accepted the average of the year, 6.5 h, the total energy production is calculated 653.25 kW/day.

The high-rate suitable areas constitute 25% of the total suitable area (Figure 6.1) The reason why the highest percentage comes out of the medium-rate areas is that the slope converges near the plain. The flat regions of the rooftops have not been taken to a high-rate class because of the extra cost of installation in flat areas.

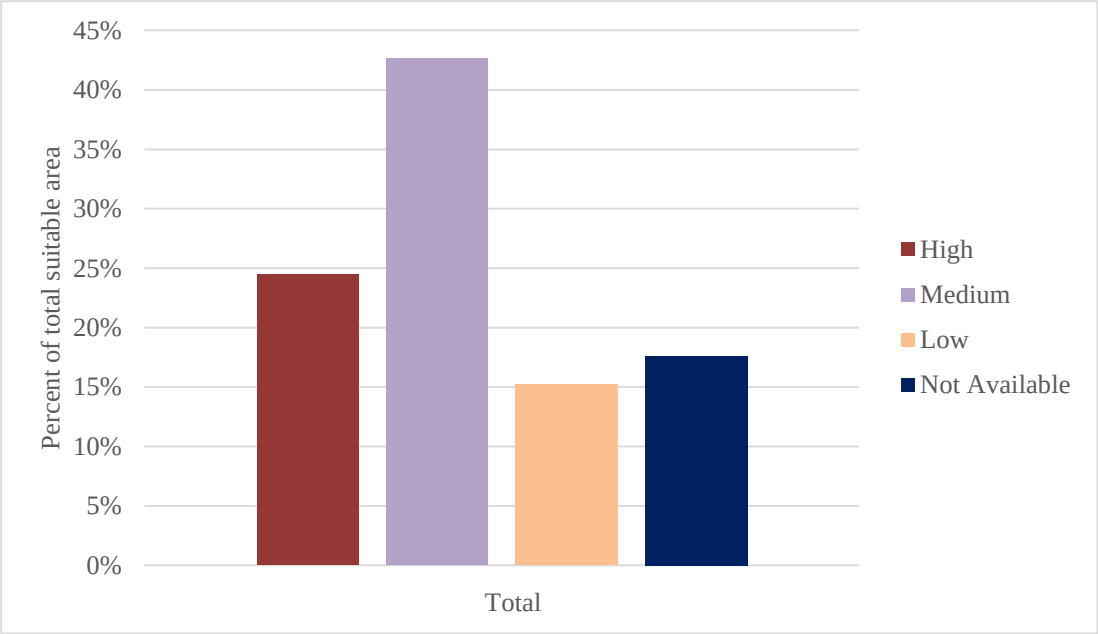

Figure 6.1 : The percent of total sutabilty ratings.

The distribution of rooftop suitability across the building ID and suitable area in percent is shown Figure 6.2. When the results of pitched rooftops are assessed, it is seen that the high-rank areas are between 17%-33% of the suitable regions on a rooftop.

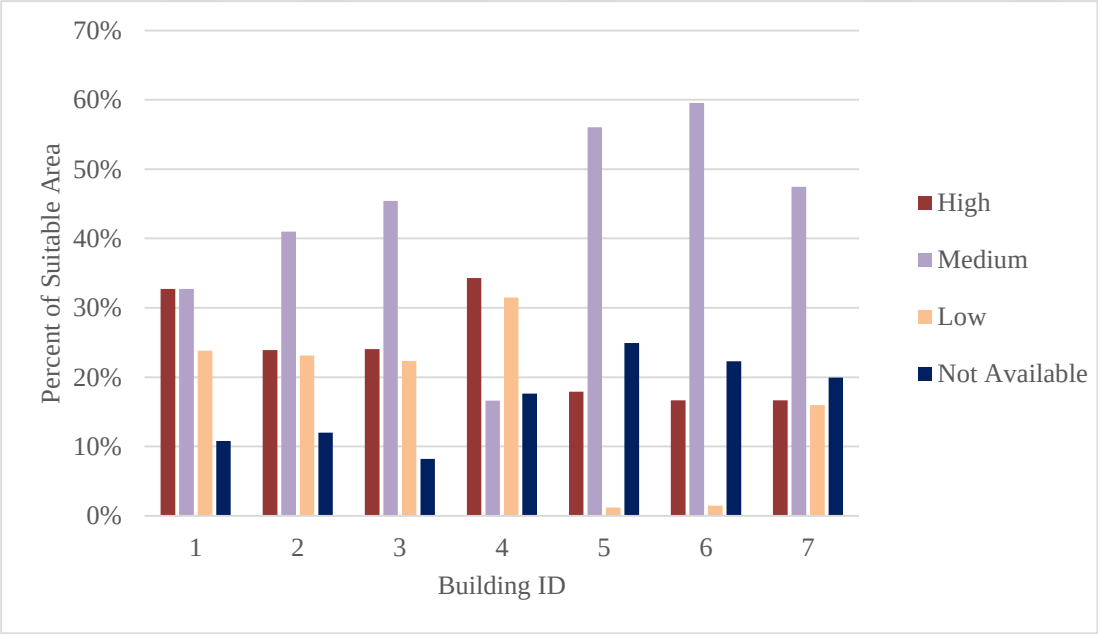

Figure 6.2 : The distribution of sutabilty ratings of pitched roofs.

The results for flat rooftops are examined for the suitability of the installation in plain regions; it is seen that between 60-70 percent is achieved (Figure 6.3).

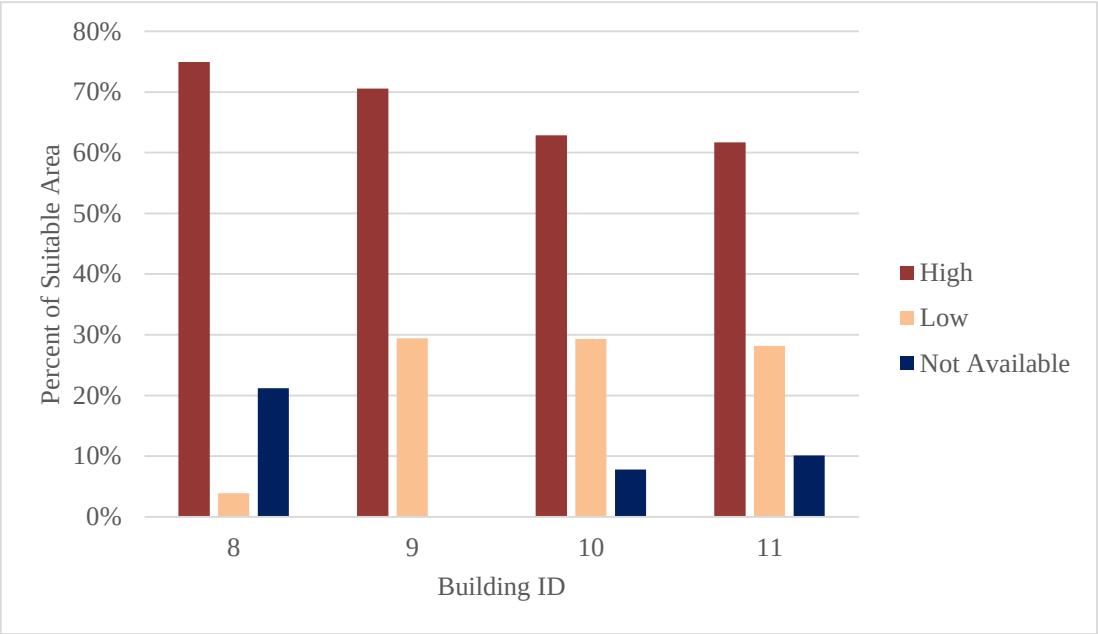

Figure 6.3 : The distribution of sutabilty of flat roofs.

The results of the slope analysis, for the pitched roofs, the most suitable rating 4 corresponded, apart from 4 and 5 rooftops, the suitability is observed to be below 30 percent (Figure 6.4). The reason why the results of 4th and 5th floors so different from others are that the average slopes are very close to the flat roof class.

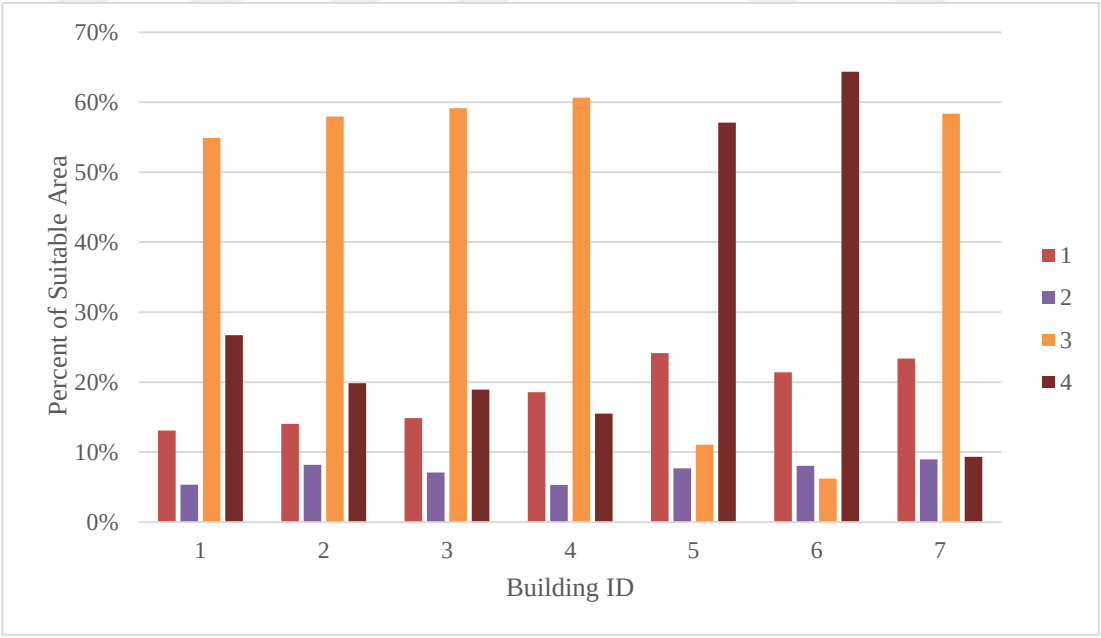

Figure 6.4 : The distribution of the slope reclassification ratings based of pitched roofs.

The highest suitability class accounts for 38% of the slope of the calculated total pitched roof area (Figure 6.5).

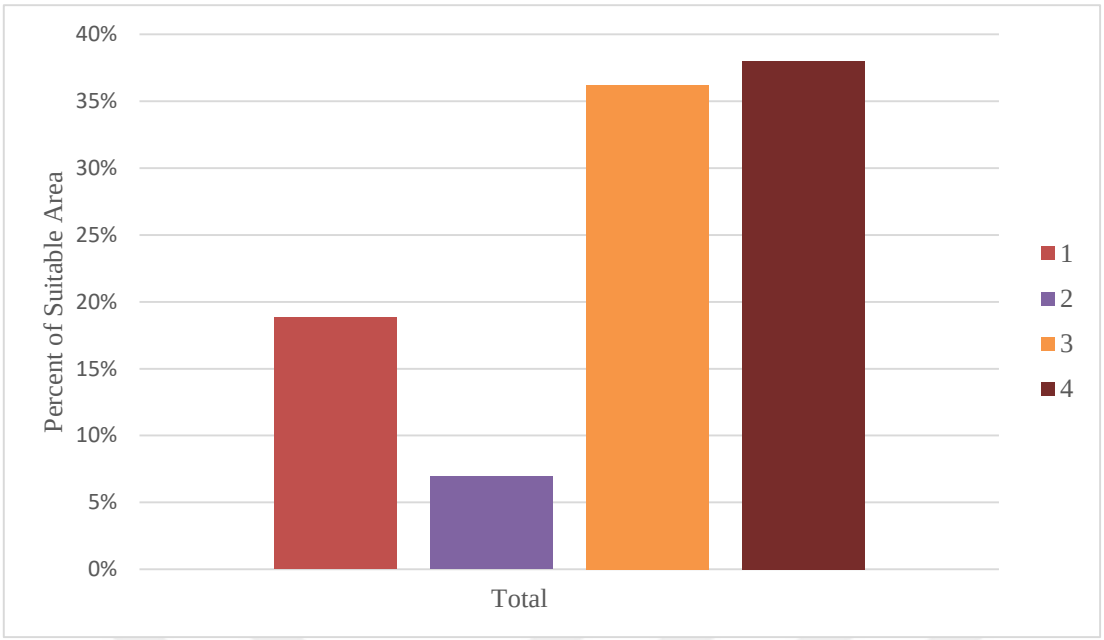

Figure 6.5 : The total distribution of the slope reclassification ratings.

The aspect percentages for each of the roof orientations are shown in Figure 6.6. The rooftops have an aspect in all directions of the rooftops; there is no much difference between these values. So, instead of commenting on this chart, it would be straightforward to comment on total percent of each direction.

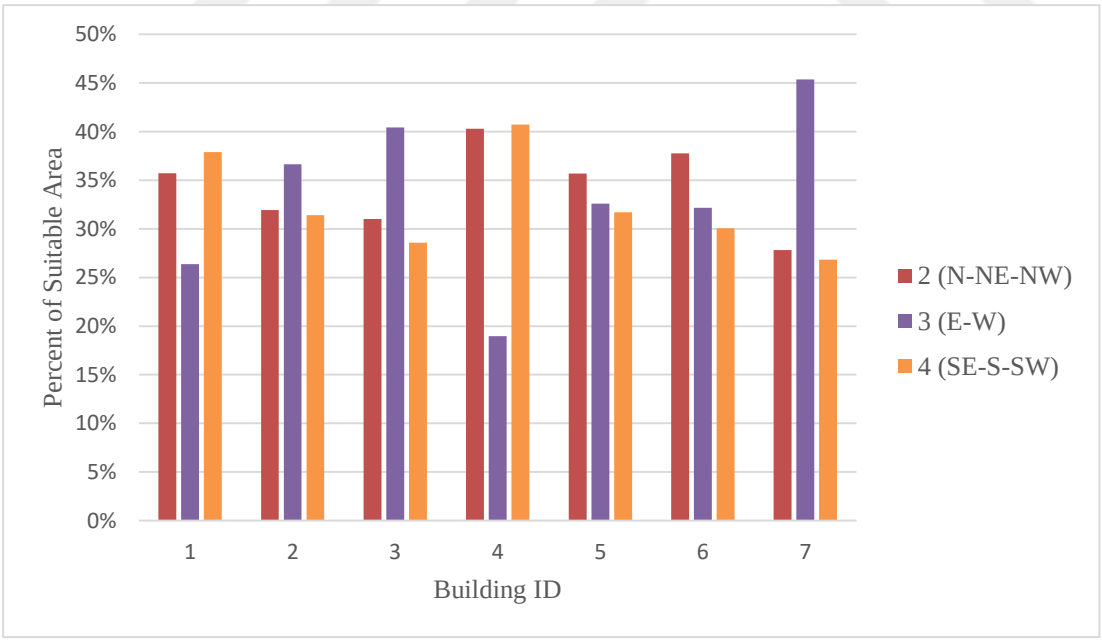

Figure 6.6 : The distribution of the aspect reclassification ratings.

When the graph was examined the total area where the aspect calculation was made, it has seen that the orientation of the north direction is the highest (Figure 6.7). Considering that the main factor influencing productivity in the orientation is to the

south, more energy can be generated from solar energy if the south direction is taken into consideration in new buildings.

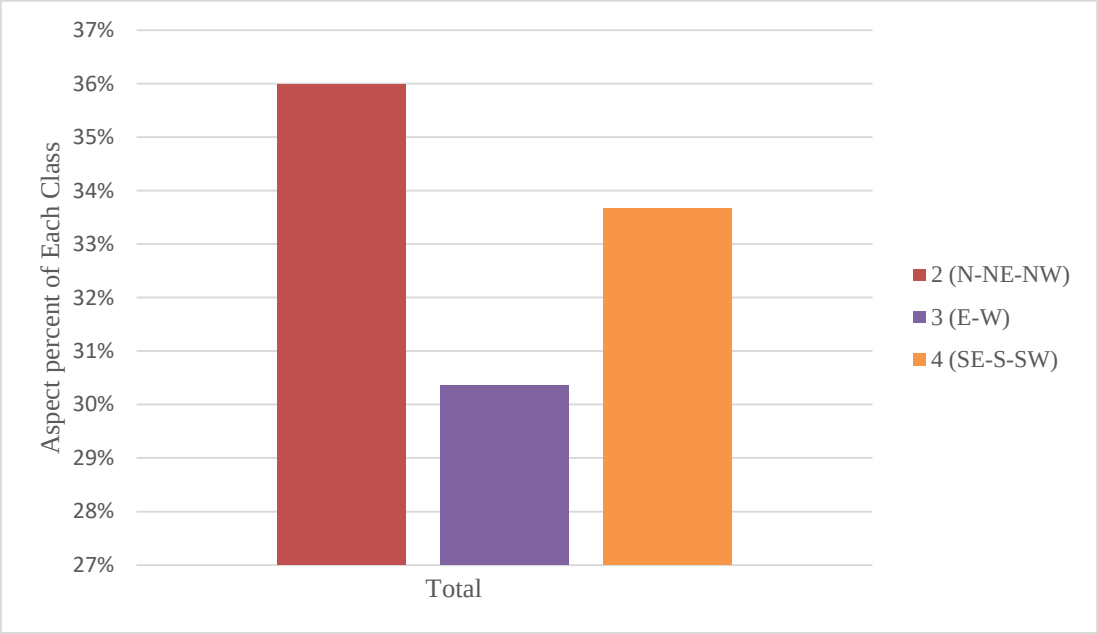

Figure 6.7 : The total distribution of the aspect reclassification ratings.

There are a number of deficiencies in the development of the model at the next stage of this study. One of the fundamental deficiencies of the model, which can not be realized in this study, is shadow analysis. The environmental impact of the shadow should be considered as a weighted overlay factor. The other rooftop components as chimney can be extracted before the special analysis.

While calculating the number of panels needed for energy production, the calculations such as the payload of buildings should be considered as well. Therefore a control regulation should be provided in order to organize such installations based on such considerations.

The model and the results can be seen as a support for the widespread use of renewable energy sources that are constantly discussed in development plans. That can be assessed to lead the way installation specialties, policy-makers, city dwellers who want to evaluate own rooftop.

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APPENDICES

APPENDIX A:

APPENDIX A

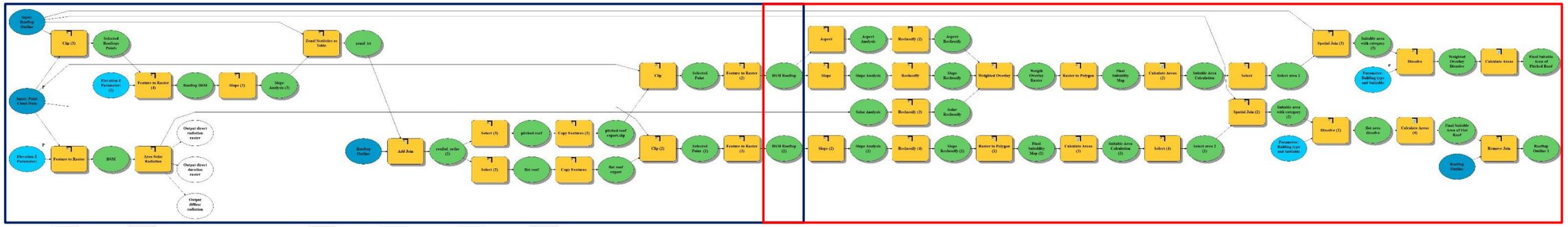

Figure A.1 : Model diagram.

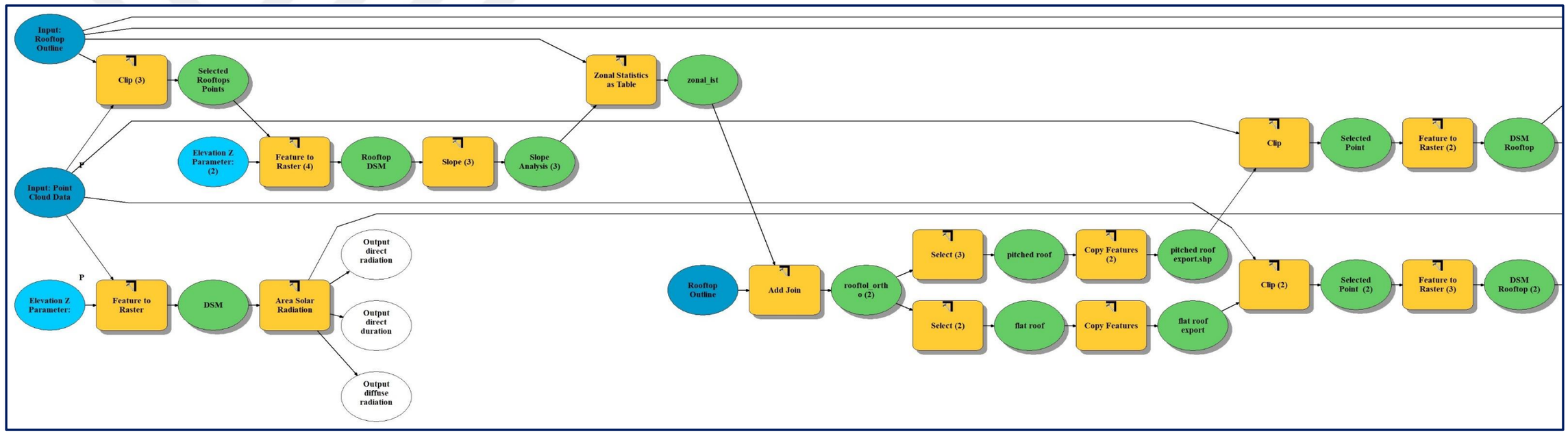

Figure A.2 : The blue section of the model diagram.

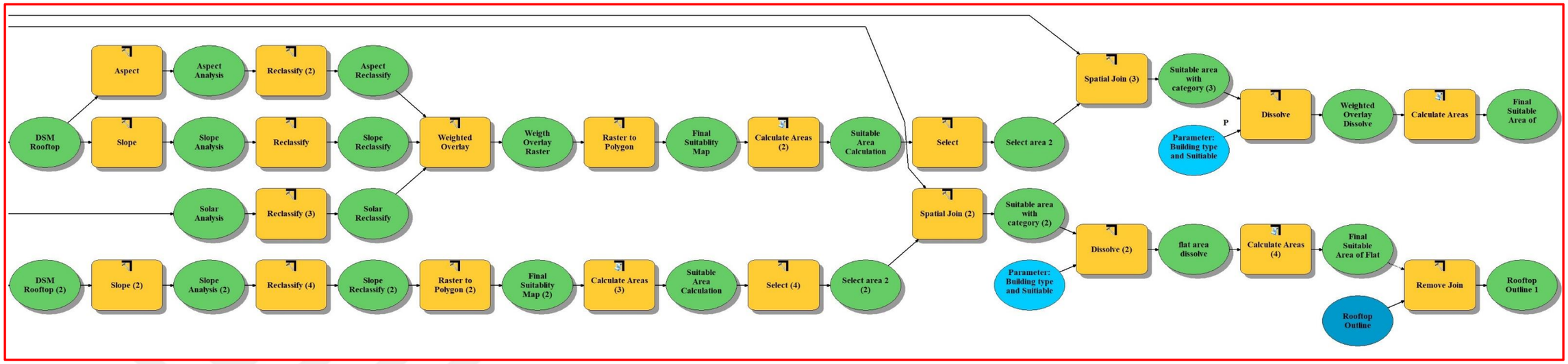

Figure A.3 : The red section of the model diagram.

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