# GIS-BASED SITE SELECTION APPROACH FOR WIND AND SOLAR ENERGY SYSTEMS: A CASE STUDY FROM WESTERN TURKEY

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## ABSTRACT

### GIS-BASED SITE SELECTION APPROACH FOR WIND AND SOLAR ENERGY SYSTEMS: A CASE STUDY FROM WESTERN TURKEY



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Many countries around the world integrated Renewable Energy Systems (RES) in their future energy plans in order to reduce negative impacts of fossil fuel consumption on the environment. However, RES may as well cause various environmental problems which are mostly related with the geographic locations of these facilities. The aim of this thesis is to create a Geographic Information System-based methodology for evaluating alternative locations for wind, solar and hybrid power plants by using fuzzy multi-criteria decision making. Environmental objectives and economical feasibility criteria for wind and solar systems are identified through Turkish legislations, previous studies, and interviews with General Directorate of Electrical Power Resources Survey and

Development. Individual satisfaction degrees for each alternative location with respect to the identified environmental objectives and economical feasibility criteria are calculated using fuzzy set theory tools. Then these individual satisfaction degrees are aggregated into overall performance indexes which are used to determine priority maps for wind and solar energy generation facilities. Finally, maps of priority sites for wind and solar energy systems are overlaid to identify suitable locations for hybrid wind-solar energy systems. The proposed methodology is applied on a case study area composed of Uşak, Aydın, Denizli, Muğla, and Burdur provinces.

Key words: Geographic Information System, fuzzy multi-criteria decision making, wind energy, solar energy, hybrid systems.

# ÖZ

## RÜZGAR VE GÜNEŞ ENERJİ SİSTEMLERİ İÇİN CBS-TABANLI YER SEÇİMİ YAKLAŞIMI: BATI TÜRKİYE'DEN BİR ÖRNEK

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Dünyada bir çok ülke fosil yakıtların çevre üzerindeki olumsuz etkilerini azaltmak amacıyla enerji planlarına Yenilenebilir Enerji Sistemlerini (YES) eklemişlerdir. Ancak YES de çoğunlukla bu sistemlerin coğrafi konumlarından kaynaklanan bir takım çevresel problemlere yol açabilirler. Bu çalışmanın amacı, rüzgar, güneş ve karma enerjisi tesisleri kurulabilecek alternatif alanların değerlendirilmesi için bulanık Çok-Kriterli Karar Verme yöntemi kullanan Coğrafi Bilgi Sistemi tabanlı bir yaklaşım geliştirilmesidir. Rüzgar, güneş ve karma rüzgar-güneş sistemler için çevresel hedefler ve ekonomik uygulanabilirlik kriterleri, geçmişte yapılmış araştırmalar, Türkiye'deki yönetmelikler ve Elektrik İşleri Etüt İdaresi ile yapılan görüşmeler sonucunda belirlenmiştir. Her bir alternatif konumun, çevresel hedefleri ve ekonomik uygulanabilirlik kriterlerini münferit sağlama derecesi bulanık mantık yöntemleri kullanılarak hesaplanmıştır. Daha sonra bu münferit sağlama dereceleri birleştirilerek toplam performans indeksleri hesaplanmıştır ve bu indeksler rüzgar, güneş ve karma sistemler için öncelikli/uygun alanların belirlenmesinde kullanılmıştır. Son olarak, rüzgar ve güneş sistemleri için oluşturulan öncelik haritaları üst üste çakıştırılarak karma rüzgar-güneş sistemler için uygun yerler belirlenmiştir. Önerilen yaklaşım Uşak, Aydın, Denizli, Muğla ve Burdur illerinden oluşan bir örnek çalışma alanı üzerinde uygulanmıştır.

Anahtar kelimeler: Coğrafi Bilgi Sistemleri, bulanık çok-kriterli karar verme, rüzgar enerjisi, güneş enerjisi, karma sistemler.

To my mother,

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| | |
|---|---|
| **AHP** | Analytical Hierarchy Process |
| **DSS** | Decision Support System |
| **EU** | European Union |
| **GIS** | Geographic Information System |
| **MCDA** | Multi-Criteria Decision Analysis |
| **MCDM** | Multi-Criteria Decision Making |
| **MODM** | Multi-Objective Decision Making |
| **OEPI** | Overall Environmental Performance Index |
| **OPI** | Overall Performance Index |
| **OSEPI** | Overall Solar Energy Performance Index |
| **OWA** | Ordered Weighted Averaging |
| **PV** | Photovoltaic |
| **RES** | Renewable Energy Systems |
| **RDM** | Regular Decreasing Monotone |
| **RIM** | Regular Increasing Monotone |
| **RUM** | Regular UniModal |
| **SDSS** | Spatial Decision Support System |

# CHAPTER 1

# INTRODUCTION

## 1.1. Overview of the Study

Through the human history renewable energy sources have been utilized. Ancient Greeks were using solar energy by orienting buildings in the way that allow sun radiation to enter inside buildings. Likewise, obtaining energy by burning wood or animal wastes, so called biomass energy, has been the major energy resource for mankind for centuries.

Today, the importance of renewable energy is commonly accepted not only due to limited fossil fuel resources, but also due to major environmental concerns associated with fossil fuel burning. Omer (2008a) states that increase in consumption of fossil fuels induce the release of greenhouse gases. Particularly, developing and industrialized countries must take some precautions in order to reduce their emission levels while preserving their economic development. In addition, Elliot (2007) points out that one of the best options is to adopt renewable energy and increase the energy efficiency in order to decrease negative impacts of climate change.

It is a fact that conventional energy systems have detrimental effects on the environment and Renewable Energy Systems (RES) seem like a solution to these problems; however, it is impossible not to affect the environment while producing energy (Tsoutsos et al., 2005). In other words, more or less, each RES has negative effects on ecology and the environment but these effects are considerably tolerable with respect to those of conventional energy systems. Therefore, renewable energy resources have advantages over conventional energy systems in terms of environmental acceptability. Nevertheless, before adopting RES, comprehensive analyses should be conducted in order to identify the best locations which are associated with highest potentials and at the same time environmentally favorable.

Decision making is an important component of investments, logistics, allocation of resources, etc. Geographers and spatial planners are interested in decision problems which are based on geographically defined alternatives. These alternatives are evaluated with respect to their spatial arrangement. Many Geographic Information System (GIS) applications provide crucial information for decision making which support site selection procedures in various research areas such as natural resources management, environmental pollution and hazard control, regional planning, urban development, and utilities management. These complex problems require simultaneous evaluation of many criteria. For this purpose, Multi-Criteria Decision Making (MCDM) can assist decision makers in selecting the best alternative (Jankowski, 1995). Accordingly, many spatial planning or management problems can be solved by GIS-based Multi-Criteria Decision Analysis (MCDA) or in other words, spatial MCDA (Malczewski, 1999).

In this thesis, a GIS-based methodology for evaluating alternative locations of wind and solar power plant installations is developed by using MCDM. The main objective is to produce a decision support system (DSS) which can assist authorities and decision makers to identify priority sites for wind and solar energy generation facilities. There are already 17 operating wind farms, 7 wind farms under construction, and 15 wind farm projects in Turkey (Web 1); in addition, new legislation associated with solar energy generation will be developed which can enhance the interest in solar power plant installations in the near future (Caliskan, 2009). Moreover, wind and solar energy investments are expected to increase in Turkey. Therefore, identification of feasible locations for future wind and solar power plants is an important issue for Turkey. The proposed methodology in this thesis may provide valuable guidance for decision makers in identifying feasible locations for wind and solar power plants before assigning licenses.

Most of the decision making procedures for site selection problems require simultaneous evaluation of multiple criteria which are used to assess the suitability degree of each alternative location. Usually it is not practical to identify a potential location as suitable or not suitable, but rather a degree of suitability may be more informative and realistic. Calculation of degrees of suitability for each alternative location may be achieved by utilization of fuzzy sets. When the criteria or objectives do not have crisp boundaries then they can be represented by fuzzy sets. The membership function of the fuzzy set allows assignment of degrees of belongingness or degrees of satisfaction for each alternative with respect to the fuzzy criteria. This facilitates the process of criteria standardization by converting statements into membership values. As a result, a set of individual satisfaction degrees are calculated for each alternative location for each criteria or objective. Then these individual satisfaction degrees are aggregated into an overall satisfaction degree which may be used in comparing the alternatives. There are number of aggregator operators commonly used to combine individual satisfaction degrees into an overall satisfaction value.

Aggregation of individual satisfaction degrees into an overall satisfaction degree will simplify the decision process. Most commonly used aggregator operators are the “and” operator (i.e. MIN), and the “or” operator (i.e. MAX). The “and” operator requires satisfaction of all of the criteria while the “or” operator requires satisfaction of any of the criteria. However, in real world problems, the decision maker may require satisfaction of “most” or “at least 20%” or “many” of the criteria. To implement such decision rules, various other aggregators have been developed. One of these aggregators is the Ordered Weighted Averaging (OWA) aggregator suggested by Yager (1988). OWA lies between the MIN and the MAX operators. OWA is based on an aggregation of ordered criteria which allows a control of trade-offs among the criteria (Eastman and Jiang, 1996). Consequently, OWA can be used to express vague preferences of the decision makers in order to obtain an overall performance for each alternative (Malczewski, 1999). In this thesis, application of all three aggregators, “and”, “or” and OWA is realized at various stages of the decision making process.

The main outcome of this thesis is a GIS-based approach for site selection of wind turbines, solar power plants and hybrid systems which are composed of wind turbines and solar power plants together, by using MCDM. A case study area, composed of

Uşak, Aydın, Denizli, Muğla, and Burdur provinces is selected and application of the proposed approach is demonstrated on this area. In the first case study, where suitable locations for wind turbine installations are identified, for each alternative location individual satisfaction degrees of environmental objectives are aggregated into an overall environmental performance index (OEPI) by using the “and”, the “or” and OWA operators. In addition to environmental fitness, wind energy potential is of crucial importance in selecting wind turbine locations. Therefore, a fuzzy set called “Sufficient potential for wind energy generation” is identified to evaluate suitability of each alternative location with respect to wind energy potential. Then the satisfaction degree of each alternative location for this fuzzy criterion is identified. Finally, the OEPI and degree of satisfaction for “Sufficient potential for wind energy generation” is aggregated by the “and” aggregator to calculate an overall performance index (OPI). Alternative locations with an OPI of 0.5 and higher are identified as priority sites (i.e. environmentally and potentially favorable sites) obtained.

The second case study is conducted for site selection of the solar power plant installations. For this purpose, OEPI is calculated by the OWA operator; however in evaluating suitability with respect to solar potential, additional criteria such as slope, proximity to transmission lines and urban areas are used as well. These criteria which are related with physical requirements and solar energy potential are referred to as economical feasibility criteria and satisfaction of each alternative location with respect to these criteria is represented by an overall solar energy performance index (OSEPI). OPI for solar power plant installations are calculated by aggregating the OEPI and OSEPI.

One of the main disadvantages of renewable energy sources is their discontinuity; in other words, dependence of energy generation on weather conditions and the climate. To overcome this drawback, hybrid systems combining more than one type of RES are suggested. Therefore, as a final analysis, priority sites for hybrid systems (i.e. systems that involve both wind turbines and solar power plants) is identified for the study area by overlaying priority maps developed for wind turbines and solar power plants.

## 1.2. Practical Use of the Study

Energy Market Regulatory Authority together with General Directorate of Electrical Power Resources Survey and Development Administration assign permits according to renewable energy potentials. However, as mentioned before, RES may have some adverse impacts on the environment. For example, wind turbines cause environmental impacts associated with noise, bird collision, visual intrusion, habitat damage, and safety (IEA, 1998). Considering increasing awareness of environmental issues around the world, it is essential to put forward a DSS for RES that uses GIS for site selection analysis.

In this thesis, a GIS-based methodology for site selection of wind and solar generation plants is developed using various aggregators together with mathematical tools of fuzzy set theory. As a case study, the proposed approach is implemented for a study area in the western part of Turkey. The results showed that the proposed methodology can assist authorities and decision makers as a spatial decision support tool. Energy Market Regulatory Authority together with General Directorate of Electrical Power Resources Survey and Development Administration can utilize the final maps where priority sites are identified while assigning licenses for wind and solar energy generation facilities.

## 1.3. Content of the Thesis

This thesis is composed of five chapters. In the next chapter, literature review associated with RES especially wind, solar and hybrid systems and MCDM is presented. The main environmental concerns of RES, renewable energy status of Turkey and the world are explained.

In the third chapter, methodology of the study is explained in detail. Identification and quantification of environmental objectives, and data collection procedures are provided. Mathematical tools such as fuzzy sets and aggregator operators used in the study are discussed in the third chapter as well.

In the fourth chapter, implementation of the proposed methodology on a study area is demonstrated. Site selection procedures for wind and solar energy generation facilities are explained in more depth using the case study. In addition, GIS applications, and data manipulations associated with the GIS-based OWA methodology are explained. In the final chapter of this thesis, a brief summary, together with conclusions and recommendations are provided. Usefulness of the results is evaluated in terms of the current renewable energy status of Turkey.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. Sustainable Energy

Today, one of the main problems that the societies are facing is energy generation and sustainable utilization. Most of the energy resources currently relied on are finite and will be depleted because of the increasing demand. In addition, there have been serious local air, water, and soil pollution problems as a result of the consumption of various energy resources. It has become clear that continuing to use fossil fuels is not wise not only due to the global impacts on climate system, but also due to both short-term and very long-term impacts on society and the ecosystem (Elliott, 2007).

While consumption of fossil fuels are increasing regardless of their adverse impacts on the environment; today, world's agenda focuses on sustainable energy systems in terms of both reliability for economic development and benefits for the environment. According to Tester et al. (2005), the definition of sustainable energy is the combination of providing energy equally to all people and protecting the environment for next generations. The RES have a common approval as a form of sustainable energy that keeps the attention recently (Omer, 2008b). In the light of these facts, RES which respond to the needs of current and future populations should be adapted.

Terms such as "renewable energy", "sustainable energy", and "green energy" can be used interchangeably. General perception towards these terms is that renewable energy sources have environmental benefits. Although it is true that the impacts of using RES are less than those of conventional energy systems, some may have significant local impacts (Elliott, 2007).

## 2.2. Renewable Energy Systems

RES have been adapted by man through the history. For example, biomass has been used for heating, cooking, and steam production for a long time. RES like wind, solar, biomass/biogas, tidal, wave, and geothermal energies are able to supply clean and efficient energy by using advanced technologies (Abulfotuh, 2007).

There are numerous economical and environmental benefits associated with RES. First, they can assist the diversification of current energy markets. In addition, they can reduce local and global atmospheric emissions and can supply specific needs for energy services, particularly in developing countries and rural areas. Furthermore, they can provide new employment opportunities, and enhance local manufacturing (Asif and Muneer, 2007).

## 2.3. Global Renewable Energy Status

It is commonly accepted that energy is necessary in order to improve the quality of life by providing basic needs such as heat, light, and power for entertainment devices and labor-saving appliances (Akpinar et al., 2008). In 2000, the main energy consumption on the earth was fossil fuels such as petroleum, natural gas, and coal with their 86% proportion (Environment Foundation of Turkey, 2006).

Energy consumption around the world is expected to rise around 2% by 2030. While compensating this energy rise, not only economical but also environmental issues need to be considered (Environment Foundation of Turkey, 2006). Renewable energy is becoming more popular around the world, because it minimizes the effect of fossil fuels, which cause greenhouse gas emissions (Ozgur, 2008). In addition, since fossil fuel sources are limited, human being will be forced to find ways of utilizing RES in the future (Akpinar et al., 2008).

According to statistics in 2005, hydropower plants had the biggest proportion among renewable energies in the world. A total of 750 GW and 66 GW power was produced from large and small scaled hydropower plants, respectively by the end of the 2005.

The wind power, on the other hand, had the second place in the world with its 59 GW power production (REN21, 2006).

Projections about 2030 indicate that the main energy source will still be petroleum and the consumption of natural gas will rise; in contrast, nuclear energy will decrease because of the cost and waste problems. It is expected that renewable energy applications will be improved during this period. Therefore, the goal of European Union (EU) countries is to produce energy from renewable resources (other than hydropower) around 150 Mtoe by 2030 (Environment Foundation of Turkey, 2006).

Moreover, both China and India have major renewable energy programs. India has extensive wind power projects and major photovoltaic (PV) solar, biomass and biogas programs. The renewable capacity of India is expected to reach 10 GW by 2012. China already has over 23 GW (th) of solar thermal capacity, and major hydro and biogas programs. By 2020, China is planning to have 30 GW of wind capacity and 30 GW of biomass plant. China, with 120 GW of renewable capacity overall, is aiming to meet around 16% of its expected electricity requirement from renewable resources by 2020 (Elliott, 2007). As can be seen from these projections, renewable energy investments are expected to expand in the future.

Increasing investments in renewable energy production is motivated by the necessity of reducing negative impacts of the climate change around the world. International Climate Change Commission states that $CO_2$ concentration in the atmosphere must be kept below 400 ppm level. Recently, the level of $CO_2$ concentration has reached 378 ppm. This is an alarming level and immediate precautions need to be taken. Therefore, EU directive 2001/77/EC encourages EU countries to produce 21% of the total electricity consumption in 2010 from renewable energy sources (Environment Foundation of Turkey, 2006).

One of the most important elements of economic development is continuous and reliable energy production. Development of energy policies that satisfy the demand while protecting the environment is of major concern. As a result of this, contribution of RES in future energy plans need to be increased considerably (Environment Foundation of Turkey, 2006).

## 2.4. Renewable Energy Status in Turkey

Energy consumption is one of the main indicators of wealth and economic development for countries. On the other hand, environmental degradation has become more apparent because of several factors such as increase in the world population, excessive consumption of resources, industrial activities, etc. Solution to environmental problems is based on adaptation of sustainable development which has close connection with renewable energy (Dincer, 1999).

Turkey supplies more than half of its energy requirement by importing energy from other countries. Additionally, one of the most important environmental concerns due to imported fossil fuel consumption is the air pollution. RES may be an efficient solution for the environmental pollution problem. Turkey has a great advantage due to its geographical location in terms of renewable energy resources availability. In conclusion, Turkey has limited fossil fuel resources and major air quality problems due to fossil fuel consumption; therefore, shifting from fossil fuels to RES might be a good alternative for Turkey (Kaygusuz and Sari, 2003).

Primary energy consumption of Turkey depended on fossil fuels in 2006 and 2007. Although petroleum and natural gas are imported from other countries, consumption of petroleum increased from 2.71% from 2006 to 2007, and consumption of natural gas increased 17.62% from 2006 to 2007. Energy production and consumption values are given in Table 2.1 (World Energy Council-Turkish National Committee, 2008).

**Table 2.1** Energy production and consumption values between 2006 and 2007 in Turkey (World Energy Council-Turkish National Committee, 2008).

| **Energy Source** | **Production** | | **Consumption** | | **Increase in Consumption** |
|---|---|---|---|---|---|
| | 2006 | 2007 | 2006 | 2007 | Percentage |
| Oil (Mtoe) | 2.1755 | 2.134 | 31.295 | 32.143 | 2.71 |
| Natural Gas (Mtoe) | 0.907 | 0.893 | 31.187 | 36.682 | 17.62 |
| Coal, Lignite, Asphaltite Mtoe) | 64.255 | 75.365 | 83.584 | 98.337 | 17.65 |
| Hydro and Geothermal (GWh) | 44338 | 6007 | 44398 | 36007 | -18.90 |
| Geothermal Heat (Mtoe) | 0.898 | 0.914 | 0.898 | 0.914 | 1.78 |
| Wind (GWh) | 127 | 355 | 127 | 355 | 179.53 |
| Solar (Mtoe) | 0.403 | 0.42 | 0.403 | 0.42 | 4.22 |
| Comb. Renew. And Wastes (Mtoe) | 4.984 | 4.85 | 4.984 | 4.85 | -2.69 |

On the other hand, Turkey has significant amount of renewable energy potential (i.e. hydro, wind, geothermal, solar power and biomass). Total renewable energy potential is the second largest domestic sources after coal, which composes 10.2% of the total primary energy sources according to 2007 statistics (Web 2). More than two third of renewable energy supply belongs to biomass, mostly combustible renewables and wastes. They are mainly used for heating in the residential areas. Hydropower composes the remaining one third of the renewable energy supply. Even though wind and solar energy have limited usage now, they are expected to increase in the near future. Current proportion of geothermal, wind and solar energy production was only 1.6% in 2007. Total primary energy supplies in Turkey can be seen in Figure 2.1 (Web 2).

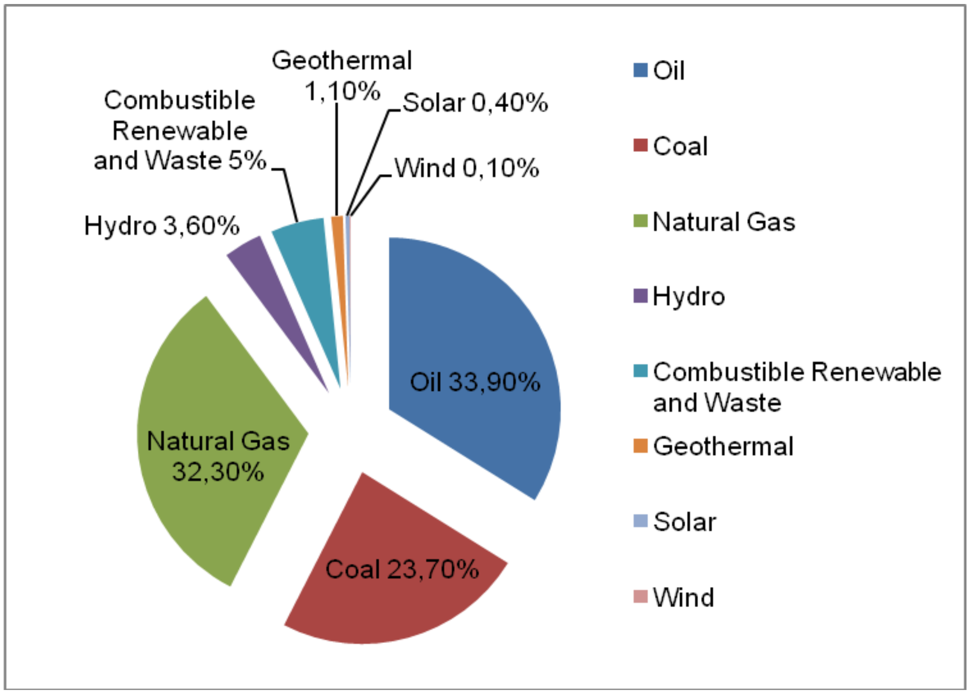


**Figure 2.1** Total primary energy supply in 2007 (Web 2)

Various researchers have investigated RES in Turkey. One of the earliest studies was conducted by Ediger and Kentel (1999) in order to identify renewable energy potentials of Turkey. Particularly, biomass energy, hydro power, geothermal energy, solar and wind energy were investigated. In conclusion, the shift from fossil fuels to RES was considered a serious alternative for Turkey in order to lessen the environmental impacts of current energy systems. In a more current study, Demirbas (2006) investigated the renewable energy facilities of Turkey such as electricity generation from biomass, hydropower, geothermal, wind and solar energy sources. In this study, biomass cogeneration was considered as a promising method for producing bioelectricity. Yuksel (2008) presented and overview of the reduction of greenhouse gas emission policies in Turkey. These policies included energy pricing, promoting energy efficiency, and using renewable energy sources. The paper concluded that supportive, realistic, and flexible policies might aid to reduce the emissions and environmental degradation. Kaya (2006) conducted a similar research about renewable energy policies in Turkey as well. The renewable energy potential of Turkey, effective utilization of the potential, energy politics, political organizations, incentive, pricing and buying mechanisms, research and development studies, barriers for development of renewable energy were investigated in the paper.

Turkey is one of the richest countries in the world in terms of geothermal potential. It is in the first place among the European countries, and seventh in the world (Akpinar et al., 2008). Over the past two decades, among the RES, Turkey has allocated the highest level of funding to geothermal energy (IEA, 2006). Currently, there are 172 geothermal fields in Turkey and total capacity of these fields is 1229 MWt. Generally, it is used for heating purposes in residential areas, and thermal facilities (Environment Foundation of Turkey, 2006).

Currently, biomass and animal waste (67.4% of Total Primary Energy Supply) are the main renewable sources consumed in Turkey. These are the main fuel for heating and cooking in many urban and rural areas (Kaygusuz, 2002). However, their consumption is expected to decline as oil, gas, coal, or electrical heating and cooking become readily available (Evrendilek and Ertekin, 2003). The contribution of the biomass resources in the total energy consumption dropped from 20% to 8% from 1980 to 2005 (Bilen et al., 2008).

Even though gross water potential of Turkey is 234 $km^3$, irregular flow condition of rivers decreases the utilization of water resources. There are 26 hydrologic basins in Turkey. Total economic hydroelectric potential of these hydrologic basins is identified as 127 billion KWh. On the other hand, total technical hydroelectric potential is identified as 216 billion KWh (Environment Foundation of Turkey, 2006). According to 2004 statistics % 35 of total economic hydroelectric potential (127 billion KWh) is being utilized, % 8 of the economic potential is under construction and remaining potential is evaluated for other projects (Web 3).

Wind and solar energy is the main topics of this thesis. Therefore these two types of renewable energy sources, their potentials and applications in Turkey are explained in detail in the following sections.

## 2.5. Wind Energy

Winds occur as a result of unequal distribution of solar heating around the world. The speed and the direction of wind can be various according to the characteristics of topography (Brower, 1992). Ackermann and Soder (2000) state that as other renewable energy recourses, people have taken advantage of wind power for many centuries until modern industrialization that caused people to deploy more reliable energy sources such as fossil fuels. However, the oil crisis which occurred in the mid-1970s, made countries to seek new energy sources in order to eliminate the dependency on fossil fuels (IEA, 2006).

In implementing new energy sources such as wind power, reducing dependency on fossil fuels was not the only concern of the countries. Another important contribution of wind energy is its assistance in terms of decreasing $CO_2$ emissions and environmental protection (Caralis et al., 2008). Wind turbines do not release any atmospheric emissions while generating power; nonetheless, there are also some negative impacts on both society and ecology (IEA, 2003).

Many researchers have been working on various aspects of wind energy such as economic benefits of wind energy, site selection procedures, environmental impacts, etc. For example, Williams et al. (2008) applied an economic input/output analysis together with Monte Carlo simulation in order to assess the economic benefits of constructing and operating a wind energy system. Lothian (2008) studied the visual impacts of wind farms in South Australia by conducting a multi participant survey.

Evaluation of wind energy systems using GIS tools became popular recently. Rodman and Meentemeyer (2006) proposed an analytical framework by using GIS to evaluate site suitability for wind turbines. The framework included rule-based spatial analysis associated with different scenarios. The suitability criteria were based on physical requirements, environmental and human impact factors. The study also included the public perception in order to determine the acceptance level of wind farms by the public. Another site selection study is conducted by Baban and Parry (2001). In that study, they proposed two different approaches for the site selection of wind farms in the UK. Wind farm location criteria were combined by using two different approaches. First, all the layers were assumed to be equally important, therefore the equal weights were given to all the criteria. In the second approach, the layers were grouped and graded from 0 to 10 according to their importance level. While 0 indicated the ideal locations, 10 represented unsuitable locations. The main goal of that study was to assist the decision making process of wind farm site selection.

Wind potential of Turkey has been studied by General Directorate of Electrical Power Resources Survey and Development Administration and wind energy atlas of Turkey is developed (Web 4). Various researchers have as well worked on wind energy potential, technological and economic aspects of wind energy. For example, Eskin et al. (2008) evaluated wind power potential of Gökçeada Island in Turkey. Wind data were collected and represented by Weibull probability density functions in order to produce wind speed distribution curves. They concluded that Gökçeada Island has wind energy potential. In a more recent study, Ucar and Balo (2009) identified the wind characteristic and wind energy potential of the Uludag region in Turkey. First, the wind speed data were collected. Then these data were analyzed by using Weibull and Rayleigh probability density functions. Technical and economic assessments were conducted and finally, three different wind turbines were selected and their electrical energy costs were calculated.

Evaluation of different wind turbine technologies is another research topic. Durak and Sen (2002) investigated the possibility of wind power application and wind turbine sites for the Akhisar area of Turkey. Different wind turbine technologies associated with local wind speed variations were evaluated. After suitable wind turbines were selected, their locations were identified by WASP software. Ozerdem et al. (2006) worked on the economic aspects of various characteristic wind turbines. They concluded that cost of the electricity generation decreases as the installed capacity gets larger.

In this thesis, the aim is to combine environmental feasibility with the wind energy potential through a MCDM process for the site selection of wind turbines. GIS and fuzzy logic tools are used to achieve this goal and the proposed methodology for the site selection process is applied for a study area which is composed of Uşak, Aydın, Denizli, Muğla, and Burdur provinces in Turkey. Proposed site selection methodology which includes combined utilization of GIS and fuzzy logic tools is a state of the art approach and its application to the study area in the western part of Turkey demonstrated its practical use.

#### 2.5.1. Wind Energy in Turkey

First Wind Energy Potential Atlas was produced by Turkish State Meteorological Service and General Directorate of Electrical Power Resources Survey and Development Administration in 2002 (Environment Foundation of Turkey, 2006). It gives a general idea about wind energy distribution in Turkey. According to the Wind Atlas, Aegean, Marmara and the eastern parts of the Mediterranean regions of Turkey have high wind potential at a height of 50 m. Today, it is assumed that current wind potential of Turkey is 88000 MW and technical potential is 10000 MW (Environment Foundation of Turkey, 2006).

First application of electricity generation from wind power was realized in 1985 in İzmir-Çeşme (Environment Foundation of Turkey, 2006). According to 2009 data of General Directorate of Electrical Power Resources Survey and Development Administration (Web 1) there are 17 operational wind farms in Turkey (see Table 2.2). Most of these wind farms are located in İzmir and İstanbul; however, the largest wind farm capacity is 120 MW and it is located in Balikesir – Samlı. In addition, there are 7 wind farms under construction. Location and capacities of these wind farms can be seen in Table 2.3. There are 15 projects with a turbine supply contract. As can be seen from Table 2.4, most of these projects are located in Balikesir and İzmir (Web 1). Capacities of wind farms under construction, operating wind farms and projects with a turbine supply contract can also be seen in Figure 2.2. In addition, there are 117 new applications for wind energy and 53 licenses were given to private companies (Web 1).

**Table 2.2** Wind Farms under Operation in 2009 in Turkey (Adopted from Web 1)

| **Location** | **Total Installed Capacity (MW)** | **Number of Wind Farm** |
|---|---|---|
| İzmir | 90.4 | 4 |
| Çanakkale | 55.5 | 3 |
| İstanbul | 86.05 | 4 |
| Balıkesir | 120 | 2 |
| Manisa | 41.4 | 2 |
| Hatay | 30 | 1 |
| Muğla | 10 | 1 |
| Total | 433.35 | 17 |

**Table 2.3** Wind Farms under Construction in 2009 in Turkey (Adopted from Web 1)

| Location | Total Installed Capacity (MW) | Number of Wind Farm |
|---|---|---|
| Hatay | 57.6 | 2 |
| İzmir | 37.5 | 2 |
| Aydın | 31.5 | 1 |
| Manisa | 140.8 | 1 |
| Osmaniye | 135 | 1 |
| Total | 402.4 | 7 |

**Table 2.4** Wind Farm Projects with a Turbine Supply Contract in 2009 in Turkey (Adopted from Web 1)

| Location | Total Installed Capacity (MW) | Number of Wind Farm |
|---|---|---|
| Balıkesir | 277.4 | 5 |
| Tekirdağ | 28.8 | 1 |
| Çanakkale | 20.8 | 1 |
| Hatay | 30 | 1 |
| Manisa | 115.6 | 2 |
| Edirne | 15 | 1 |
| İzmir | 180 | 4 |
| Total | 667.6 | 15 |

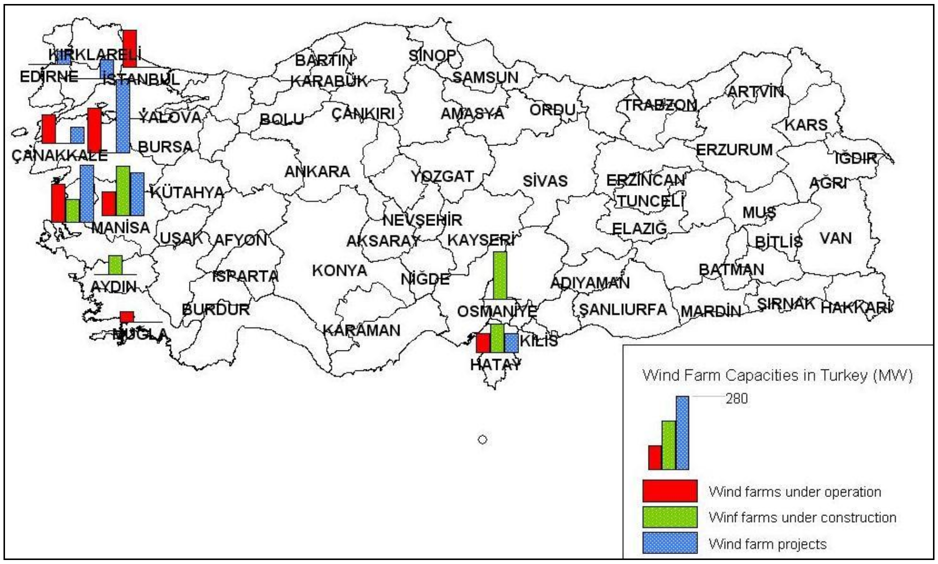


**Figure 2.2** Wind farm capacities in Turkey (Adopted from Web 1)

### 2.5.2. Environmental Impacts of Wind Energy

Various environmental impacts of wind energy are commonly accepted by scientists. These impacts may be listed as effects on animal habitats (particularly bird collisions), noise generation, visual impact, safety issues, and electromagnetic interference. In this thesis, environmental impacts associated with wind energy are utilized in developing environmental acceptability of alternative locations for wind turbine installations. Fuzzy environmental objectives are defined and satisfactions of each alternative location with these objectives are calculated. Then, these individual satisfaction degrees are used to estimate an OEPI for each alternative location. Therefore, the environmental impacts are explained in detail in the following paragraphs.

Average bird collision to each wind turbine is in the range of 0.1 to 0.6 per year (Web 5). The rotating blades of wind turbines cause blur image on bird’s eyes, therefore, birds construe that image as safe to go through, which leads to bird collisions (Morrison and Sinclair, 2004). In order to eliminate bird collisions, wind turbines should be located at a certain distance from bird flyways. According to Yue and Wang (2006), wind turbines must be located at least 500 m away from wildlife conservation areas. Another suggestion (Clarke, 1991) is that locating wind turbines at a minimum distance of 300 m away from bird habitat can provide bird protection.

A further impact of wind energy on habitat is noise. Although there are some regulations in terms of acceptable noise levels which depend on perception of communities, it is not easy to establish common noise principles (Wrixon et al., 1993). Different authorities have different noise criteria, one of which claims that wind turbines should be located at least 400 m away from nearest habitat (IEA, 1987). In addition, other authorities such as Tester at al. (2005); Ramirez-Rosado et al. (2008); Yue (2006) stated that wind turbines should be located at least 500 m  away from nearest habitat.

Visual impact, another side effect of the wind turbines, varies between individuals. According to Ramirez-Rosado et al. (2008) since the wind energy is constructing the clean energy image, some people might enjoy seeing them; on the other hand, the other people might consider it has adverse impacts on urban landscape. Baban and Parry (2001) stated that wind turbines should be located 2000 m away from large settlements because of aesthetic concerns.

Even though a number of serious accidents have occurred, the safety record of wind energy is generally good that most of the accidents are due to poor management or noncompliance with safety regulations (Wrixon et al., 1993). Voivontas et al. (1998) suggested that minimum distance from towns must be 1000 m for safety reasons and the same criteria is valid for reducing the visual impact as well. Nguyen (2007) studied wind energy in Vietnam and concluded that a 2000 m buffer zone around city centers is unsuitable for wind development because of safety and visibility considerations.

According to Nguyen (2007), one other restriction that needs to be taken into account while selecting the location of wind turbines is their proximity to airport areas due to safety and visibility reasons. Nguyen (2007) suggested that wind turbines should be at least 2500 m away from the nearest airport area. In addition, General Directorate of Civil Navigation in Turkey sets some restrictions about structures around airports. Basically, these restrictions aim to protect flight security, human lives, and property. In the first 3000 m zone there should not be any structure such as hospitals, schools or common buildings that may cause reflection. Buildings that are less than 45 m height are allowed with in the second 3000 m zone (General Directorate of Civil Navigation, 2007).

Moreover, wind turbines cause electromagnetic interference by scattering the electromagnetic waves from navigation and telecommunication systems (IEA, 2003). Although television and radio signals may be affected by wind turbines which are located in a 2-3 km zone around the largest installation, today, cable networks or line-of-sight microwave satellite transmissions are eliminating the electromagnetic interference effect of wind energy (IEA, 1987).

### 2.6. Solar Energy

Solar energy is another ancient energy resource which had been used through the history. One of the earliest developments on solar technology was made by Lavoisier who achieved to construct a 1700˚C solar furnace in the eighteenth century (Tester et al., 2005). Today, wide ranges of solar technologies are available such as solar thermal heating systems, solar PV systems, and solar buildings (Brower, 1992).

Solar PV systems allow generating power via PV cells which take advantage of solar radiation. Solar thermal heating systems, on the other hand, produce hot water and electricity by flat plate collectors or solar thermal electric plants (IEA, 2008). Solar buildings may have passive or active systems. Rationale of passive systems is to design the buildings more efficiently so that the building can exploit from sunlight (Brower, 1992). The difference between active and passive systems is that active systems deploy the collector in order to utilize the solar energy (Tester et al., 2005).

A vast amount of research has been conducted about solar energy in recent years. The researches emphasize mostly on, feasibility, environmental impacts and economic aspects of solar energy systems. For example, Paoli et al. (2008) compared conventional energy systems with thermal and PV power plants. The study stressed out the energy efficiency of solar power technologies. Martins et al. (2008) investigated the feasibility of the solar energy applications for electricity generation in Brazil. Solar energy potential was evaluated by using SWERA database. The study concluded that the grid connected PV systems can provide an important contribution to current energy system.

Economical and environmental feasibility of solar systems are other popular research areas. Bhuiyan et al. (2000) worked on economic feasibility of stand-alone PV power systems in rural areas of Bangladesh. The study presented the life cycle cost of PV systems for rural areas. The analyses indicated that PV systems are economically feasible in remote areas of Bangladesh. Tsoutsos et al. (2005) presented an overview of potential adverse impacts of solar energy systems on the environment. These impacts were identified as noise and visual intrusion, greenhouse gas emissions during manufacturing, water and soil contamination, energy consumption, labor accidents, impacts on archaeological sites or on sensitive ecosystems. Carrion et al. (2008) proposed an environmental decision support system for site selection of grid-connected PV power plants. Multi-criteria analysis and Analytic Hierarchy Process (AHP) were used to identify optimal sites in GIS environment.

Solar energy research in Turkey is mainly conducted by General Directorate of Electrical Power Resources Survey and Development Administration, Turkish State Meteorological Service, The Scientific and Technological Research Council of Turkey (Web 6). In addition, various researchers worked on solar energy potential in Turkey, and performance of solar energy systems. For example, Bulut and Büyükalaca (2007) proposed a model in order to estimate the daily global radiation. This model was expected to provide guidance for designers of energy related systems. Sozen et al. (2004) studied the solar-energy potential in Turkey using artificial neural-networks (ANNs). Kurklu et al. (2002) developed a new type of solar collector and tested its short term thermal performance. In another very recent study, Muneer et al. (2008) investigated potentials and limits of solar thermal applications in Turkish textile industry. It was discussed that adaptation of new instruments would assist to overcome the obstacles. In addition, detailed life cycle assessment and economic aspects of solar water heater was presented in the study.

Site specific solar systems studies have also been carried out by various researchers in recent years. Yumrutas and Kaska (2004) investigated the performance of experimental solar assisted heat pump space heating system located in Gaziantep, Turkey. Ulgen (2006) examined the tilt angle of solar collectors in order to determine optimum tilt angle in İzmir, Turkey. Estimation of the total global solar radiation on a tilted surface was accomplished by using a mathematical model. Celik (2006) investigated the current status of PV energy and evaluated the techno-economic feasibility of grid-connected PV systems in Turkey, Ankara. An hourly basis simulation was conducted to estimate the performance of the PV systems. Analyses indicated that theoretically designed grid-connected PV system is more expensive than the grid electricity.

In this thesis, different environmental acceptability and economic feasibility are investigated for solar PV systems to identify priority sites for solar power plant installations in the western part of Turkey. The study area is composed of Uşak, Aydın, Denizli, Muğla, and Burdur provinces. Environmental acceptability and economic feasibility are combined in GIS environment using fuzzy MCDM procedure.

### 2.6.1. Solar Energy in Turkey

Geographical location of Turkey allows utilization of solar energy. While annual average solar radiation is 3.6 kWh/m$^2$-day, total radiation period is approximately 2640 hours, monthly solar energy values are given in Table 2.5. According to the solar energy evaluations South Eastern Anatolia Region has the highest solar energy potential and Mediterranean Region has the second highest solar energy potential in Turkey.

**Table 2.5** Monthly average solar energy values in Turkey (Web 6)

| Months | Monthly Total Solar Energy (3,6 kWh/m$^2$-day) | Insolation duration (hour/day) |
|---|---|---|
| January | 51.75 | 103 |
| February | 63.27 | 115 |
| March | 96.65 | 165 |
| April | 122.23 | 197 |
| May | 153.86 | 273 |
| June | 168.75 | 325 |
| July | 175.38 | 365 |
| August | 158.40 | 343 |
| September | 123.28 | 280 |
| October | 89.90 | 214 |
| November | 60.82 | 157 |
| December | 46.87 | 103 |
| Total | 1311 | 2640 |
| Average | 3.6 | 7.2 |

However, in order to ensure better solar energy potential values, General Directorate of Electrical Power Resources Survey and Development Administration and Turkish State Meteorological Service have been collecting the solar values since 1992. As a result of ongoing measurements, actual solar energy potential in Turkey is expected to be more than 20-25% previous values (Web 6). In addition, today, General Directorate of Electrical Power Survey and Development Administration provides solar energy potential atlas which enables to visualize the geographic distribution of solar energy potential (Web 7). In spite of this high potential, solar energy generation is only realized by flat plate solar collectors. They are mostly employed in the sunny coastal regions in order to produce domestic hot water (Kaygusuz and Sari, 2003).

There are other solar energy devices such as PV modules and solar collectors that enable electricity generation from solar power. Because of the high cost of these applications, they are only used by the Ministry of Environment and Forestry for forestry observation towers, Turkish Telecommunication Companies for transfer stations, the Highway Board Department for emergency calling, traffic management systems, General Directorate of Electrical Power Resources Survey and Development Administration for demonstration applications and various research associations (most of which are off-grid) in Turkey (Ozgur, 2008).

### 2.6.2. Environmental Impacts of Solar Energy

Even though solar energy systems may provide clean and safe energy to the public and industries, similar to any other manmade project, solar energy systems have certain impacts on the environment. Most specific environmental concerns associated with these systems depend on dimensions (size and nature) of the projects that generally cause loss of amenity (Tsoutsos et al., 2005).

Different solar energy systems have different kind of impacts on the environment. For example, PV systems do not generate any noise or chemical pollutants during utilization (Tsoutsos et al., 2005). However, other environmental concerns most of which are related to their life-cycle exist for PV systems. These concerns are air pollution generated during transport, manufacturing and waste management PV modules after decommissioning. On the other hand, direct impacts of PV systems are related to land use, and visual impact (Tsoutsos et al., 2005).

Visual impact is highly depending on the surroundings of the PV systems. If PV modules are deployed near the area of natural beauty, visual impact on this area will be inevitable (Tsoutsos et al., 2005). In addition, there are further restrictions which are set by General Directorate of Civil Navigation in order to provide flight security. For example, in the first 3000 m zone there should not be any structure such as hospitals, schools or common buildings that may cause reflection. Buildings that are less than 45 m height are allowed with in the second 3000 m zone (General Directorate of Civil Navigation, 2007).

Impact of PV systems on land use depends on the area of land covered by the PV systems, the type of the land (cultivable land might be damaged by large scale installations), and distance from areas of natural beauty or sensitive ecosystems, and the biodiversity (Tsoutsos et al., 2005). In addition, agricultural lands in Turkey are protected by Soil protection and Land Use Law (Law number: 5403). According to Turkish Soil protection and Land Use Law, agricultural area must be protected in order to sustain natural functions of the land. However, if there is not any alternative location for certain facilities such as defense, oil and natural gas research, mining activities for public interest, temporary places after emerging natural disasters, agricultural lands can be used for development (Law number: 5403).

Carrion et al. (2008) developed an environmental decision support system for the site selection of grid-connected PV modules. Environmental, orography, location, and climate criteria are used to identify priority sites. These criteria are subdivided into factors; in environmental criterion, there are two factors which are land use, and visual impact of PV modules. Land use restrictions are based on environmental protection laws.

According to Carrion et al. (2008) land use restrictions are based on environmental protection laws. Mostly preferable locations for PV systems are fields without vegetation. Environmental protection laws in Turkey are associated with forest areas, national parks, natural protection zones, coastline and wetlands. According to the Forest Law in Turkey, any kind of construction in forest area is forbidden. However, Ministry of Environment and Forestry can allow constructions for defense, infrastructure, communication, oil research, natural gas, solid waste disposal institutions, if these activities are highly necessary to build on forest areas for public interest (Law number: 6831).

Similar to forest areas, constructions at national parks are restricted by legislation in Turkey. According to National Parks Legislation, the structures which have adverse impacts on habitat cannot be built on national parks since these areas have to be preserved. Only the structures for visitors, management and research are allowed (Official journal number: 19309). In addition, national protection zones are identified with respect to Environmental Legislation and international conservation agreements in order to protect the natural assets and take precautions to decrease environmental degradation. These areas are considered ecologically sensitive and only constructions which are compatible with the nature such as restaurants, shops, maintenance and repair facilities etc. are allowed (Official journal number: 20341).

PV systems have another adverse impact on ecosystem which is related to release of toxic and hazardous materials. Since PV modules contain toxic and hazardous materials, abnormal plant operations may cause the discharge of these toxic materials into the environment. However, proper site selection by taking into account of flora and fauna on the adjacent areas can decrease the risks (IEA, 1998). Therefore, wetlands need to be considered for the site selection of PV systems, since they have high ecological values and biodiversity. According to the Legislation of Wetlands, there must be at least 2.5 km buffer zone to protect ecological and topographic features of these areas (Official journal number: 21937).

There are further restrictions about coastal zone in Turkish Law (Law number: 3621). According to the legislation, coastal zone is divided into two zones. The first 50 m zone is allocated to green belts, and recreational areas. The second 50 m zone is for small scaled touristic places, roads, open car parks, and treatment facilities (Official journal number: 21374).

Other solar energy systems, such as solar thermal heating systems, solar thermal electricity, have land use and visual impact considerations as well. In addition, solar thermal systems are using coolant water in order to generate electricity. This may lead to pollution of water resources during thermal discharges. Coolant water contains liquid water or molten salts therefore; release of these materials might induce a health hazard (IEA, 1998). Since PV systems are investigated in detail in this thesis, other solar energy systems are not explained further here.

## 2.7. Hybrid Energy Systems

As energy demand is increasing around the world, RES such as solar PV systems and wind energy had become more important (Ahmed et al., 2009). Even though RES are attractive options for energy sectors, the main disadvantage of these systems is their dependence on weather and climatic conditions. However, this problem can be dealt with integration of two or more RES which is called a hybrid system. Thus, the weakness of one system might be compensated by the strengths of the other sources (Hongxing et al., 2009).

There are many studies in the literature providing examples of hybrid RES. For instance, Liu and Wang (2009) discussed the current energy status in China and presented an application of wind–solar energy hybrid generation systems in China. The study verified that wind-solar hybrid systems can moderate the inconsistent outcome due to the weather and climatic changes. Celik (2002) compared PV–wind hybrid energy systems with single PV and wind systems with respect to techno-economic conditions of these systems. The study presented that performance of an optimum combination of the hybrid PV–wind energy system is better than either single system. Reichling and Kulacki (2008) proposed a model for the performance of a hybrid wind-solar power plant in Minnesota. Economic feasibility of hybrid plants were compared to wind farms and concluded that the wind-solar hybrid plants provide financial benefits. Ulgen and Hepbasli (2003) investigated power generation from solar-wind hybrid plants in Izmir, Turkey. First, a model was developed to identify wind, solar and hybrid power resources. Then, hourly, daily, and monthly analyses of solar and wind power integration were carried out. As a result, it was concluded that hybrid systems could contribute to more efficient utilization of these resources.

## 2.8. Environmental Management and GIS

Environmental research and policy-oriented environmental management are both related to geographic framework. Clearly, high proportion of the required data for environmental management is geographic data. Recently, significance of computational applications in GIS has been increasing in this field. Environmental management applications have been great contributor in the development of GIS throughout its history. Moreover, GIS and geographic data are indispensible for research, teaching and policy making in environmental disciplines (Goodchild, 2003).

Contribution of GIS to environmental management varies according to the purpose. GIS may be used just as a provider of information or as a true analytical instrument. At the lowest sophistication level, GIS is a tool in order to produce visual maps for decision-makers and researchers. In a more sophisticated way, it allows to conduct fully integrated information systems which can be a sufficient decision making tool (Rodriguez-Bachiller and Glasson, 2004). For example, GIS applications in environmental management have been used for environmental monitoring by using satellite images such as the Land Cover Maps of Great Britain (Fuller and Groom, 1993) and monitoring wetland changes in East Africa (Haack, 1996). Some mapping systems provide combination of environmental data with related information such as, the promotion of sustainable tourism in the Mediterranean region (Giavelli and Rossi, 1999), or mapping the biomass distribution by using ecological data in Southern New Mexico (Phinn et al., 1996).

More specifically, GIS can be linked to external models for environmental management which is one of the most popular applications of GIS (Rodriguez-Bachiller and Glasson, 2004). Environmental modeling is an essential field of scientific research in order to assess and predict the impacts of human activities on environment. For example large-scale industrial, energy, construction, water resources, or agricultural projects may have impacts on the environment. As can be seen, most of the environmental problems are related to spatial dimensions and spatial data are the basic elements of GIS. It is obvious that integration of these two fields of research is a promising idea (Fedra, 1993).

GIS can assist at different stages in order to construct different environmental models, sometimes at the design stage or the estimation stage (Rodriguez-Bachiller and Glasson, 2004). For example, Johnston et al. (1996) used GIS to model ecological processes, Arsenau and Lowell (1992) constructed a model for monitoring the forests, McKenney et al. (1999) standardized a model for solar radiation by using a Digital Elevation Model. Coskun and Alparslan (2009) proposed an environmental model to investigate the temporal changes of land use and water quality changes of Omerli Watershed in İstanbul, Turkey. Remote sensing and GIS techniques were used to analyze water quality and land use assessments as well. Brown and Affum (2002) proposed a GIS-based environmental modeling system in order to identify the environmental impacts of road traffic plans. It is suggested that using this model might assist planners to test both environmental impacts associated with transportation plans and efficiency of network plans. Store and Jokimaki (2003) developed a method to generate integrated habitat suitability index which is based on GIS. This method enables to produce spatial ecologic information associated with habitat requirements of different species. Mas et al. (2004) proposed a model in order to predict the spatial distribution of tropical deforestation. Satellite images were used to generate deforestation risk assessment maps.

As a result, GIS is an essential tool in environmental management. Even though it is not the only computer application associated with this field, it plays a vital role in the development of environmental policy and environmental decision making (Goodchild, 2003). Thus GIS tools are used in this thesis to evaluate economical and environmental feasibility of alternative locations for wind and solar energy generation systems.

### 2.9. Spatial Decision Support Systems

Basic problems which have specific solution methods are easily solved by using GIS tools; however, when problems become complicated, the simple logic may not be enough for the solution. DSSs are developed to resolve more complex situations, and GIS is used as the DSS development platform to satisfy such needs (Rodriguez-Bachiller and Glasson, 2004).

Spatial decision making problems do not always have to be structured or unstructured in real world but may lie on somewhere between these two extreme cases. These decisions are called semi-structured. Cooperation between computer-based systems and decision makers is required in semi-structured decisions. Most of the real life spatial decision problems are semi-structured (Malczewski, 1999). Spatial Decision Support Systems (SDSSs) can cooperate and organize all of the activities and interests with respect to decision maker’s purpose. Such a system simplifies the interaction of ideas, evaluation of results and decisions. In other words, it assists to share the information among decision makers and consideration of the multiple criteria in a more organized and logical way (MacDonald and Faber, 1997). The DSS developed in this thesis is a semi-structured decision support system. The model which is developed in ArcView 3.3 model builder allows some tasks to be programmed, since the processes through the solutions are not repeated regularly and each stage of the process is different than another. However, user input is required to accomplish the remaining tasks.

GIS can provide a wide range of analyses and visual demonstration of the cartographic data. Nevertheless, it does not assist the user to select the suitable functions for a certain purpose, or to interpret the results (Seffino et al., 1999). Considering spatial decision processes, a series of tasks are required in order to obtain results. First of all, decision makers need to construct the database relations and models, determine the appropriate modeling strategies, select the related data sets, and decide the analyses flow. Finally results of analyses can be demonstrated and solutions of the problems can be interpreted (Zhu et al., 1998). GIS can contribute to SDSS by generating different kinds of maps associated with the choice of a given set of models and decision procedures (Seffino et al., 1999). However, additional modeling tools for more complex analytical methods can turn GIS into a well-developed SDSS (Silva and Eglese, 2000).

Many researchers have been trying to develop SDSS models using GIS. For example, Dragan et al. (2003) propose a SDSS in Ethiopia. The study is based on determining new locations of crops with respect to their capacity in order to reduce soil erosion. GIS software IDRISI 32 is used to develop SDSS and the direct involvement of local stakeholders is used to identify constrains and factors.  Banai (2005) suggests a SDSS prototype based on land resource sustainability for urban development. MCDA and analytical hierarchy process are used together within GIS environment. This prototype includes public policies and sustainability criteria in order to identify the best locations for future sustainable urban development. Chang et al. (2008) conducted a two staged study. First, they developed a SDSS for waste management in south Texas using GIS functions to produce thematic maps. Then, they used fuzzy MCDM as a tool to represent the environmental, biophysical, ecological, and socioeconomic variables. Sikder (2009) proposed a knowledge-based decision support system in order to indentify the adaptability of crops at a given agro-ecological zone. A flexible interface was produced in GIS which leads to an increase in efficiency in crop management and land use planning. In a very recent study, Lejeune and Feltz (2008) developed a decision support tool in GIS to assess environmental and landscape constraints associated with wind farms. In this study, 40 environmental and landscape criteria and three constraint levels (exclusion, highly sensitive and sensitive) were identified in order to obtain the overall constraints map for wind energy constructions in Belgium.

In this thesis, a spatial decision support tool was developed in GIS environment to identify the feasible locations for future wind and solar energy development. Various layers were created according to environmental objectives and economical feasibility criteria. In addition, several GIS tools were produced to assist decision makers to facilitate the decision process.

### 2.10. Multi-criteria Decision Analysis (MCDA)

Either individuals or a group of people faces with spatial decision making in everyday life. Choosing a new development area, selecting a new residential area, or managing the infrastructure system requires spatial organization. Most of the individual spatial decisions are made by taking into account the heuristics or the past experiences. However, more reliable and analytical methods are needed for organizations to support spatial decision making (Jankowski et al., 2001).

The rationale of MCDM models is based evaluation of multiple criteria to find a solution of a problem with multiple alternatives. These alternatives can be evaluated by their performance characteristics, in other words, decision criteria (Jankowski et al., 2001). Basically, MCDM enables the decision maker to evaluate a set of alternatives according to conflicting and incommensurate criteria. A criterion is a generic term which may be constituted by both attributes and objectives. Therefore, MCDM can be classified into two groups: Multi-attribute decision making (MADM) and multi-objective decision making (MODM) (Malczewski, 1999).

In the MADM approach, each alternative is evaluated with respect to various attributes and final choices are made among potential alternatives. On the other hand, MODM is based on the decision maker’s objectives which can be a statement about the desired state of the system. Several different attributes might represent objectives. In other words, MODM problems deal with the objectives which require establishing specific relationships between attributes of the alternatives (Malczewski, 1999).

Further classification depends on decisions under certainty and decisions under uncertainty. If decision makers have adequate knowledge about all the variables and parameters of the problem, the decision can be classified as decision under certainty which is also called deterministic decision-making. However, many real world decisions are very complex to be deterministic. Thus decision associated with a problem involving random and uncertain variables, and vague or incomplete data are considered as decision under uncertainty. Two types of uncertainty may exist in a decision situation: uncertainty due to vague, incomplete or limited information or variability due to randomness. As a result, both MADM and MODM problems can be classified further into probabilistic and fuzzy decision making problems. Probability theory or statistics are used to solve problems involving random variables. On the other hand, fuzzy set theory tools are used to solve problems that involve vague and incomplete data. Presence of incomplete information leads to results that may not be represented by crisp numbers but rather with degrees. These types of problems are handled with fuzzy sets theory (Zadeh, 1965).

As mentioned before, MCDM provides solutions to decision problems which have multiple alternatives. Decision rules are used to choose the most preferred alternative between several options. In other words, decision rule is a course of action that allows selecting best alternative from a set of alternatives. This procedure provides overall assessment of alternatives by integrating the data and decision maker’s preferences (Malczewski, 1999). Although significant numbers of decision rule approaches are presented in the literature, there are limited applications of combined utilization of GIS and MCDM. The weighted summation, ideal/reference point, and outranking methods are the examples of such approaches which allow integration of MCDM and GIS (Malczewski, 2006).

One of the widely used decision rules is AHP which can be used in two different ways in GIS environment. In the first approach, weights are assigned to each attribute map layer, and then weights are aggregated by using weighted additive combination methods. This method is more practical if large numbers of alternatives are involved (Eastman et al., 1993). In the second approach, the AHP principle is used to aggregate the priority for all level of hierarchy structure including the level of representing alternatives. In this case, small number of alternatives is needed (Jankowski and

Richard, 1994). There are many examples in the literature about AHP. For example, Hill et al. (2005) investigate the new methods for selecting suitable sites for various land uses in Australia. MCDA and AHP are combined and used to determine biophysical, economic and infrastructure suitability of land use. New interfaces are produced in the ArcInfo Grid GIS environment. In another very recent study, Ercanoglu et al. (2008) used AHP to assess landslide vulnerability in the West Black Sea Region of Turkey. Ying et al. (2007) used AHP with GIS in order to evaluate eco-environment information system in Hunan Province, China. The aim of this study was to identify regional features of eco-environment and main environmental problems of the study area. Natural environment, disaster, environment pollution and social economy factors were proposed as evaluation index system. As a result, the regional eco-environmental information system database and evaluated the eco-environmental quality of Hunan Province were established.

Another method which allows combined utilization of MCDM and GIS is the ideal point approach. The ideal point approach is based on the set of alternatives which are ordered with respect to their separation from an ideal point. This point corresponds to a hypothetical alternative (decision outcome). The best alternative is the closest to the ideal point. The ideal point approach is an attractive methodology if relationships between attributes are complex to verify or test (Malczewski, 1999).

One of the most popular GIS-based MCDA approach is the weighted summation method. The main reason of its popularity is that the approach is easy to understand and apply within GIS environment, therefore, very appealing for decision makers. This method has usually been employed together with Boolean operations. OWA approach provides an extension and generalization of the Boolean operation and the weighted summation procedures (Malczewski, 2006). In this study, together with "and" and "or" operators for aggregation of individual satisfaction degrees into an overall satisfaction value, the OWA operator is used as well.

OWA is a general aggregator operator which includes three different types of aggregation operators: (i) "and" operator which refers to the intersection of fuzzy sets, (ii) "or" operator which refers to the union of fuzzy sets; and (iii) the averaging operator (Tabesh, 1992; Eastman et al., 1993). Most commonly used aggregation operators are "and" and "or" operators and they are used to represent two extreme cases:

“Satisfaction of all the desired criteria” and “Satisfaction of any of the desired criteria”, respectively (Yager, 1988). However, in some cases, decision makers may want to perform an aggregation which lies in between these two extreme cases. For such situations, Yager (1988) proposed the OWA function which combines “and” and “or” operators and refers to it as the “orand” operator. The rationale of this application is to aggregate the attributes not by classical weighted average but by ordered position of the attributes.

OWA aggregation method has been used by researchers on various types of decision making problems. For example, Makropoulos and Butler (2006) proposed an extended version of OWA method, called spatial ordered weighted averaging. This method was applied on water supply network and the problem is defined as vulnerability to leakage. Boroushaki and Malczewski (2008) used OWA and AHP together in a hypothetical site suitability problem in order to identify the best parcel for development. Valente and Vettorazzi (2008) integrated OWA into GIS to identify priority sites for forest conservation in Brazil. AHP was also used in this study to assign the importance to each criterion. These criteria are proximity to forest patches; proximity among forest patches with larger core area; proximity to surface water; distance from roads; distance from urban areas; and vulnerability to erosion. It is concluded that the OWA method is flexible and easy, in addition, it provides a better understanding of the alternative land-use suitability patterns. Bell et al. (2007) proposed GIS-based OWA in order to analyze spatial distributions of local health outcomes. GIS was used to construct the index, and OWA was used to validate deprivation indices that were constructed using more qualitative data sources. Yanar (2003) integrated fuzzy logic system into ArcGIS software in order to allow users to include linguistic quantifiers into GIS-based spatial analyses. The proposed system assists to approximate complex ill-defined problems in decision-making processes.

Decision making using fuzzy set theory tools has been used in various research areas. OWA is one of the most widely used tools of fuzzy set theory. However, combined utilization of OWA and GIS tools does not have too many applications. In this thesis, “and”, “or”, and OWA operators are used to aggregate fuzzy environmental objectives and economical feasibility criteria in GIS environment. The proposed approach enables evaluation of both environmental and economical criteria and construct of suitability maps according to preferences of decision makers.

# CHAPTER 3

# METHODOLOGY

In this section, methodology of the study is explained comprehensively for the site selection procedures proposed for wind turbines and solar power plants. The flowcharts of the proposed methodologies are given in Figure 3.1.

First, environmental objectives and economical feasibility criteria for wind and solar energies are identified. Then, morphological features of the study area which are spatial distribution of wind and solar energy potentials, vector data (i.e. boundaries, water bodies, coastline, forest areas, agricultural areas, national protection zones, national parks, airports, urban and rural areas, transmission lines, bird migration paths, etc), and raster data (i.e. slope) are collected and processed in order to obtain spatial data layers. The next step is representation of environmental objectives as fuzzy sets for both solar and wind energy. Individual satisfaction degrees of each alternative location with respect to the identified environmental objectives are computed in GIS using membership functions of these objectives. Then, OEPI are calculated for each potential location by aggregating individual satisfaction degrees of each environmental objective. Spatial MCDM, specifically “and”, “or”, and OWA aggregators are used to combine individual satisfaction degrees.

The procedures used for evaluating potentials of wind and solar energies are slightly different. For wind energy, in addition to environmental objectives, acceptability in terms of wind energy potential is represented as a fuzzy set. Sufficient wind energy potential map is produced in GIS using the membership function of this fuzzy set. On the other hand, for solar energy, together with solar energy potential map, various other criteria such as slope of land, proximity to transmission lines and urban areas - all together referred to as economical feasibility criteria - are taken into account for assessment of suitability of each alternative location for a solar power plant. Hence, each one of the economical feasibility criteria is represented by a fuzzy set. Then, the individual satisfaction degrees of each economical feasibility criteria are aggregated into an OSEPI by using spatial MCDM. Finally, for wind energy, the OEPI is combined with the sufficient wind energy potential map to generate priority sites for wind turbine installations while for solar energy, the OEPI is aggregated by the OSEPI and priority sites for solar power plants are identified. After priority site maps of solar power plants and wind turbines are obtained, these two maps are overlaid to identify suitable locations for hybrid RES (i.e. RES composed of both wind turbines and solar power plants).

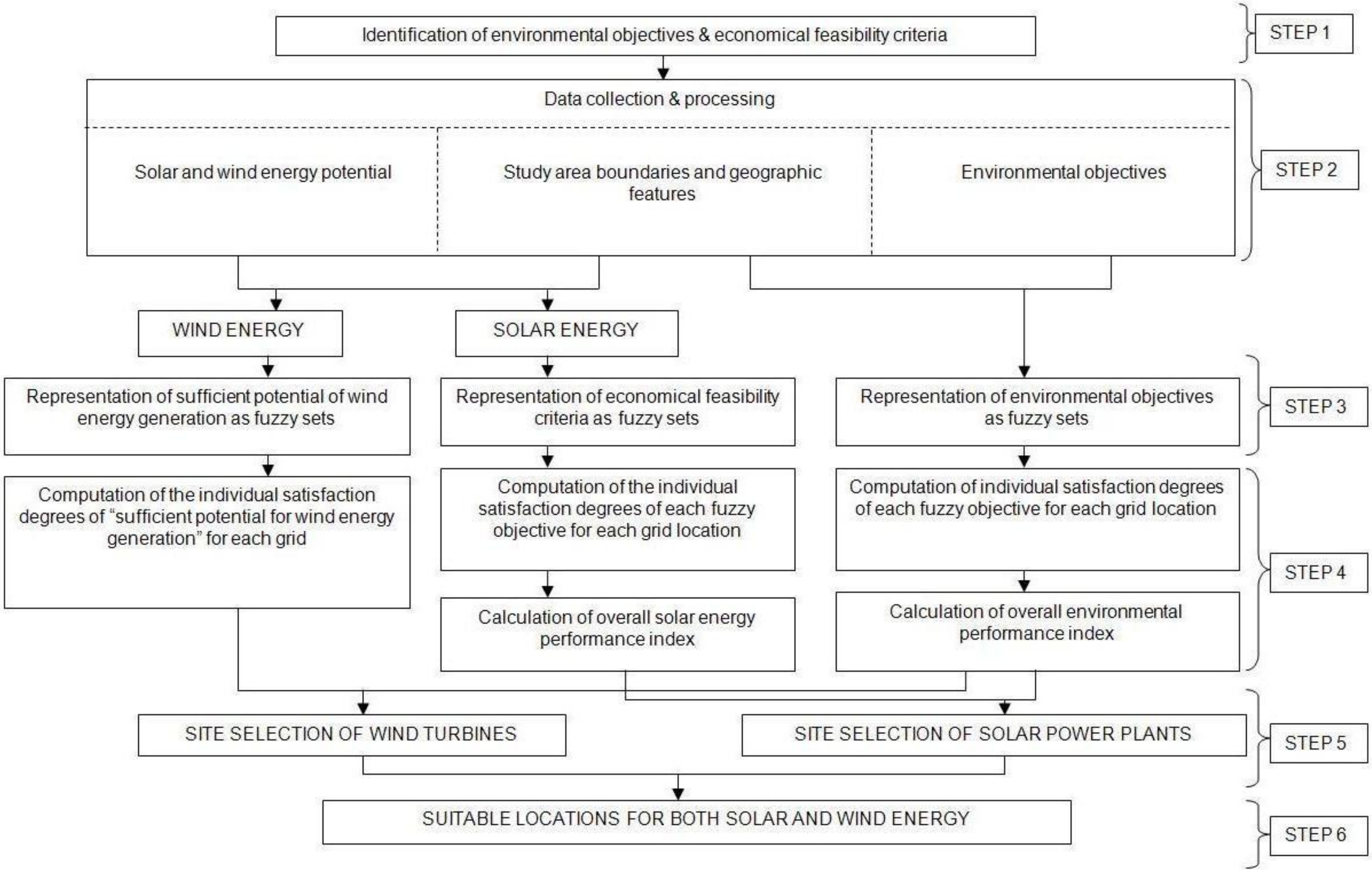


**Figure 3.1** Methodology of the study

### 3.1. Identification of Environmental Objectives and Economical Feasibility Criteria

As the first step (see Figure 3.1), environmental objectives associated with solar and wind energy generations are identified through a detailed review of literature and current Turkish laws and legislations. Environmental regulations associated with national parks, noise management, wetland protection, airports, and coastline are investigated. Restrictions with respect to these regulations are utilized to identify environmental objectives and these objectives are quantified with certain criteria. The details of this process for solar and wind energies and identified environmental objectives are provided in Section 4.2.1.1 and 4.3.1.1 of this thesis, respectively.

In addition to environmental objectives, energy potentials need to be evaluated in determining suitable locations for RES, as well. Wind and solar potentials of alternative locations are determined through literature review and interviews with the General Directorate of Electrical Power Resources Survey and Development Administration. Additional economical feasibility criteria related with solar energy generation are identified from previous studies as well. The details of this process and economical feasibility criteria are provided in Section 4.2.1.1 of this thesis. It should be emphasized here that additional environmental objectives and economical feasibility criteria may be identified in accordance with specific site conditions, energy policies, selected technologies, specific requirements of the country, etc. New criteria can easily be included in the analysis through the proposed methodology as long as required data exists and is available for the analysis.

### 3.2. Data Collection and Processing

Since, evaluation of the identified environmental objectives and economical feasibility criteria require various geographic data, the second step involves data collection and processing (see Figure 3.1). Study area boundaries, wind and solar energy potentials of the study area, settlement areas, roads, water bodies, slope, bird migration paths, natural reserves, airports, transmission lines, are among the collected spatial data.

Solar and wind potential atlases for Turkey were developed by the General Directorate of Electrical Power Resources Survey and Development Administration. Wind energy potential atlas provides wind resources information at 50 m height. This potential map was generated by using global atmospheric circulation model, medium-scale numerical weather model and the micro-scale wind flow analysis model (Web 4). On the other hand, solar potential atlas was produced according to solar radiation values which were collected between 1985 and 2006. This model was produced by using GIS “ESRI Solar Radiation Model” (Web 7).

Data concerning natural reserves (i.e. national parks, natural protection zones, forests, wetlands) of study area are collected from several government institutions. National park boundaries, forest areas, and wetland protection zones are acquired from the Ministry of Environment and Forestry. Data concerning agricultural lands within the study area are obtained from Ministry of Agriculture and Rural Affairs. In addition, latitude and longitude of national protection zones are declared in the official journals (Official journal number: 20702, 26371, 24055, and 26551) are utilized. This data is obtained in point format and converted to regions in GIS environment. Similarly latitude and longitude of wind turbines within the study area which were declared by Energy Market Regulatory Authority (Web 8) are converted to point data in GIS environment. Other data, including transmission lines, settlement areas, roads, city and district boundaries, water bodies, rivers, airports, slope, and bird migration path, were obtained from the Basarsoft Company and previous individual studies. Detailed information about the collected data is given in Table 3.1. As can be seen in Table 3.1 required data are obtained in different data formats. These data are transferred into ESRI Shapefile in order to be used in ArcGIS 9.2. which has the capabilities to conduct the required analyses.

**Table 3.1** Content of the required data.

| Data | Data format | Obtained from | Scale |
|---|---|---|---|
| Solar and wind potential atlases | MapInfo TAB | General Directorate of Electrical Power Resources Survey and Development Administration | Cellsize: 500 m |
| National park boundaries, wetland protection zones | ESRI Shapefile | Ministry of Environment and Forestry | 1:25 000 |
| Forest areas | Geodatabase | Ministry of Environment and Forestry | 1:100 000 |
| Agricultural area | ESRI Shapefile | Ministry of Agriculture and Rural Affairs | 1:100 000 |
| National protection zones | Latitude Longitude | Official journal number: 20702, 26371, 24055, and 26551 | Latitude Longitude |
| Transmission lines, settlement areas, roads, boundaries, water bodies, rivers, airports | MapInfo TAB | Basarsoft company | Vector data |
| Operating wind turbines | Latitude Longitide | Energy Market Regulatory Authority | Latitude Longitude |
| Bird migration path | ESRI Shapefile | Arikan, 2009 | 1:250 000 |
| Slope | ESRI grid | Arikan, 2009 | Cellsize: 100 m |

MCDM procedure allows evaluation of various alternatives with respect to a number of criteria. Thus, alternatives need to be identified first. In this thesis, the alternative locations are identified as follows: The whole study area is divided into 250 m by 250 m grids and each grid represents an alternative location for the power plant installation. The main reason for selecting this grid size is that scales of the obtained data are not suitable for a finer grid. In other words, while distance between each grid decreases, data accuracy decreases as well. The accuracy of the results is dependent while the utilization of the proposed methodology is not dependent on the grid size. When finer data becomes available a finer grid can be used. Another important parameter in selecting the grid size is the time required for the computations. When finer grid is used computation time increases significantly. In addition to these factors, distances required by the environmental objectives and economical feasibility criteria are also considered in selecting the grid size. If finer data is available, there are not any restrictions for the computation time and evaluation criteria necessitates then a finer grid can be used to conduct the analysis. In the case studies of this thesis, for the sake of demonstration a 250 m by 250 m grid is used.

250 m point grids were created for the whole study area in ArcGIS 9.2 software. ArcView 3.3 model builder was utilized in order to facilitate the grid creation processes. Two types of vector data which are polylines and polygons need to be converted to 250 m point grids. For this purpose, two new tools are created; “Polygon to Grid” tool and “Ployline to Grid” tool. One of them converts polygon data to 250 m point grids which is called “Polygon to Grid” and given in Figure 3.2. Figure 3.2 shows the model diagram and the application process of grid creation from polygon data.

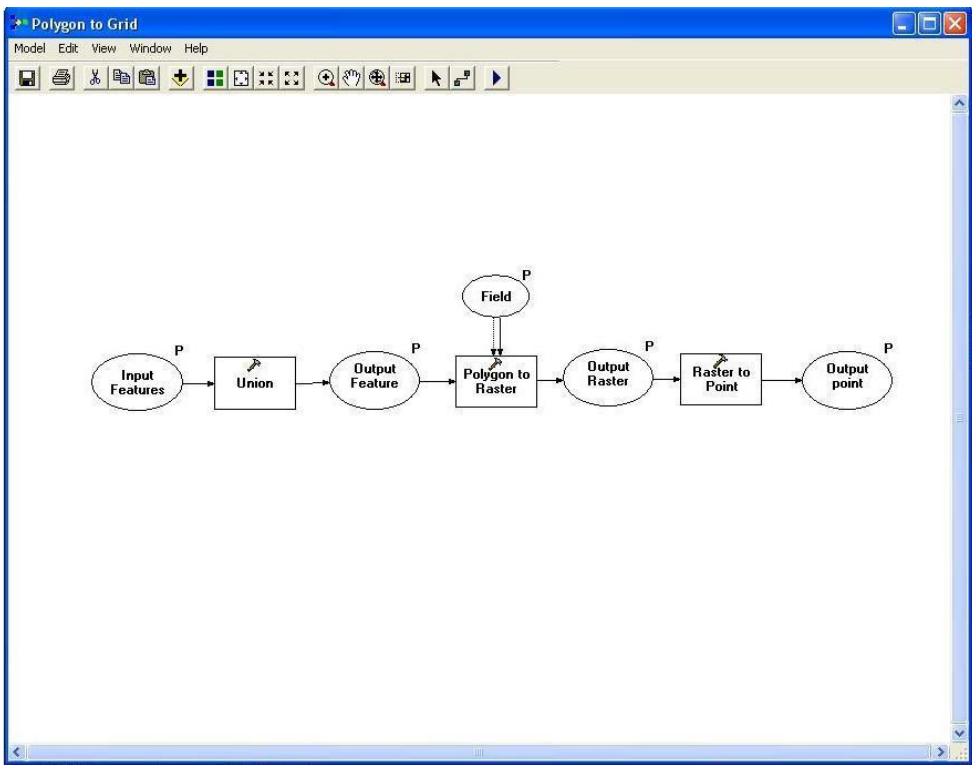


**Figure 3.2** Model diagram for “Polygon to Grid” tool

“Polygon to Grid” tool allows the user to choose either multiple layers or a single layer to create grids. The main advantage of using model builder is that multiple steps of a procedure can be accomplished by a single tool. Instead of selecting three different tools (union operator, polygon to raster, and raster to point) the user deals with only one. The model builder is especially useful for the procedures that need to be conducted repeatedly.

"Polyline to Grid" tool is created to convert polyline data to 250 m point grids. Figure 3.3 shows the model diagram and the application process of grid creation from polygon data. This tool is utilized in converting rivers and electricity transmission lines to point grids which will be used to calculate nearest distances.

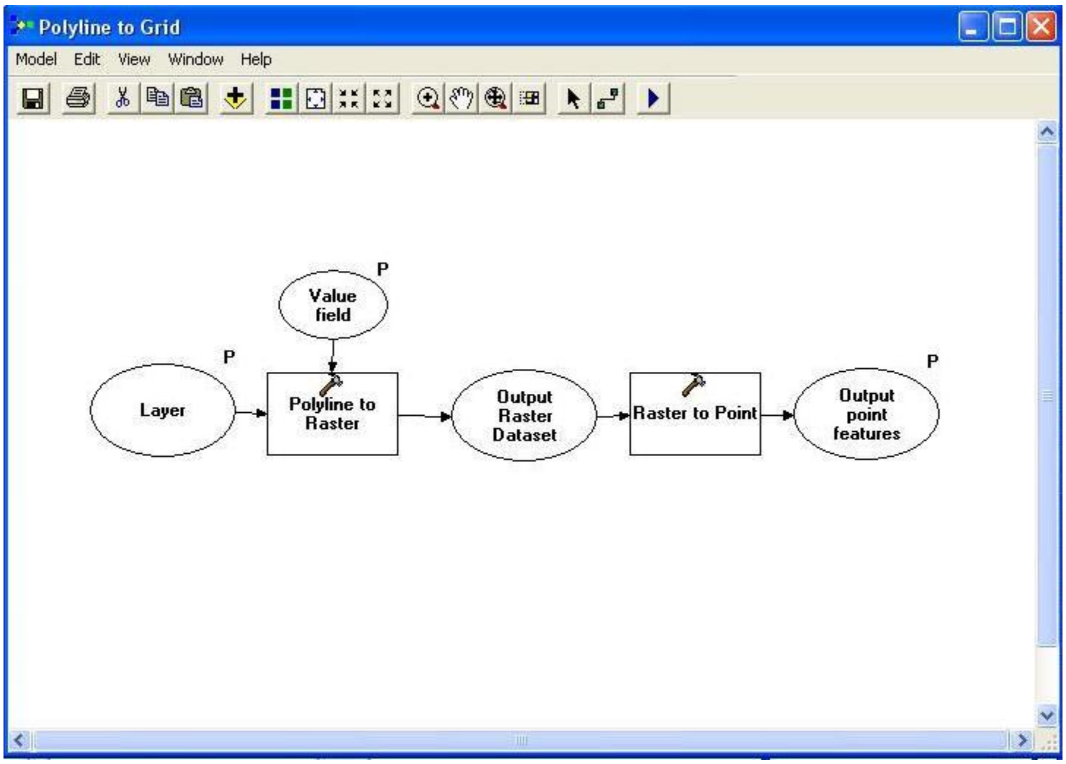


**Figure 3.3** Model diagram for "Polyline to Grid" tool

To evaluate individual satisfaction degrees of each alternative location with respect to identified environmental objectives or economical feasibility criteria, a separate layer is created in GIS environment. For example, since one of the environmental objectives requires the noise generated by wind turbines not to disturb the population, in the "Noise" layer, data related with housing areas is stored. In order to use these data in generating OEPI for wind farms, layers are converted from raster data to point data. These point grids allow us to determine the distances between the centers of each grid to the closest housing area.

For example, Figure 3.4 demonstrates the calculation of the nearest distance for an alternative location which is represented as a blue dot to the housing areas which are represented by green stars. After all the distances from the alternative location to the surrounding housing areas are calculated the smallest of these distances is selected and the result is stored in a new column in the GIS database (see Figure 3.5). Then the stored nearest distance is used to calculate the individual satisfaction degree of the alternative location for the noise objective. As a final step, the individual satisfaction degree is stored in a newly created column. Similar analyses are conducted for each layer associated with the environmental objectives and economical feasibility criteria. Then, the data is exported to excel files to apply aggregation operation to calculate degrees of satisfactions for “Satisfaction of the most of the environmental objectives”, “Satisfaction of any of the environmental objectives”, and “Satisfaction of all of the environmental objectives”. Finally, Excel data is imported back to GIS to visualize the results.

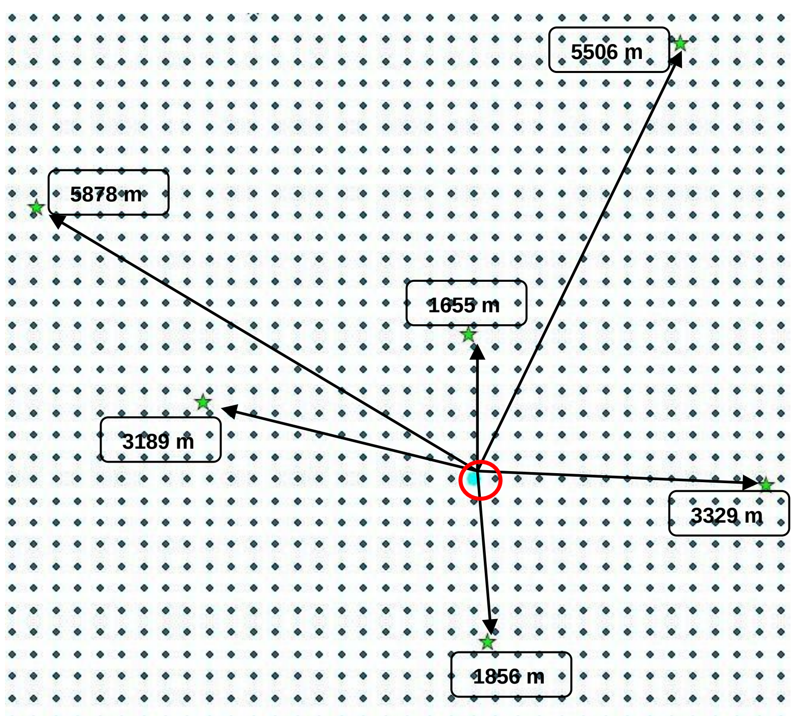


**Figure 3.4** Calculation of the nearest distance for a single alternative location

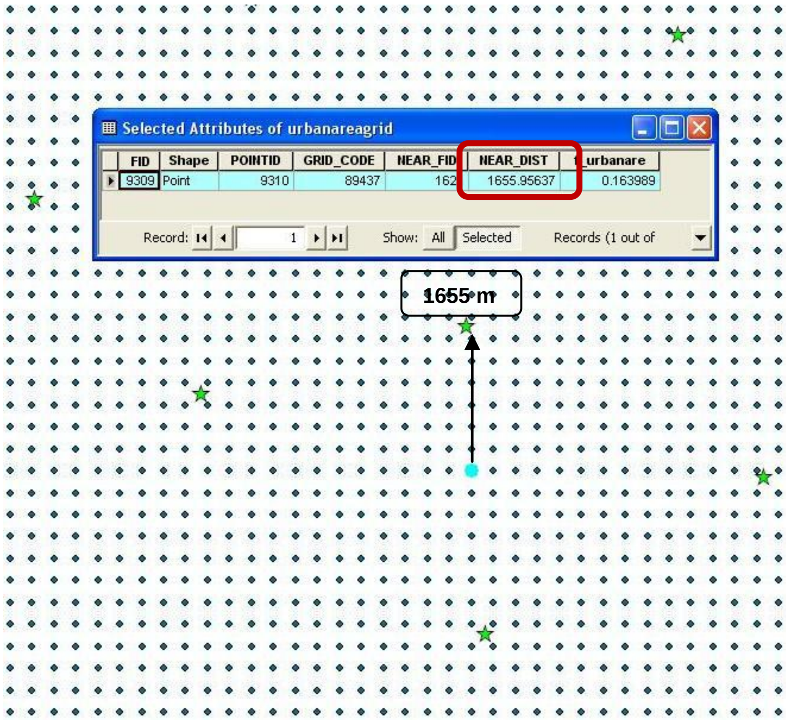


**Figure 3.5** Nearest distances in GIS database

Since this process need to be repeated for each environmental objective and economical feasibility criteria, and the sequence of applications is complex and time consuming, new tools are developed in GIS environment to conduct the necessary steps of the proposed approach by using model builder capability of ArcGIS 9.2 software. These new tools are called “Grid Calculation” and “Import Data”.

“Grid calculation” tool can be used to calculate necessary distances for each alternative required by the environmental objectives or economical feasibility criteria and to calculate individual satisfaction degrees of each alternative with respect to each objective or criteria. This new tool also allows exporting satisfaction degrees of each environmental objective into Excel and conducting necessary calculations in Excel. Figure 3.6 demonstrates the model diagram and the application process.

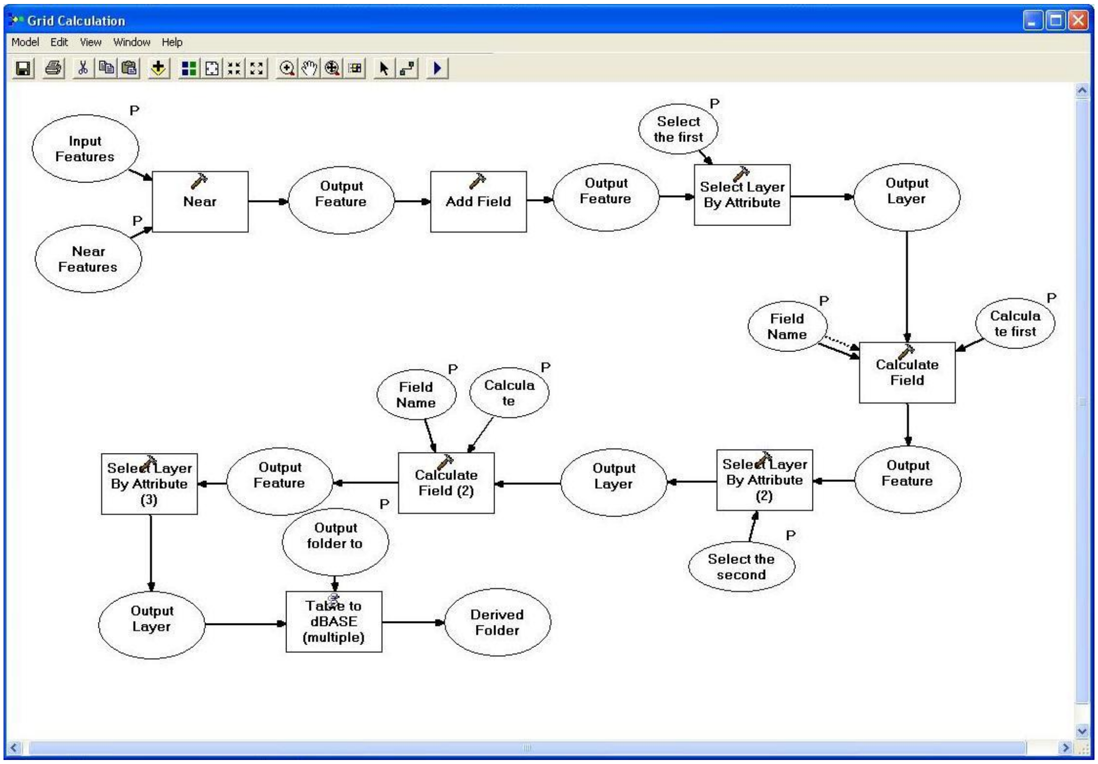


**Figure 3.6** Model diagram for "Grid Calculation" tool

After calculations related with OWA aggregation are performed in Excel, the results need to be imported back to ArcGIS to generate OEPI maps. Since there are many alternatives (approximately 723950 grid points), and Excel files have limited storage capacity (i.e. 65536 rows), 12 separate excel files are used to conduct necessary calculations. Importing each file to ArcGIS one by one is time consuming. To save time and simplify the procedure a tool called "Import Data" is generated in the model builder (see Figure 3.7).

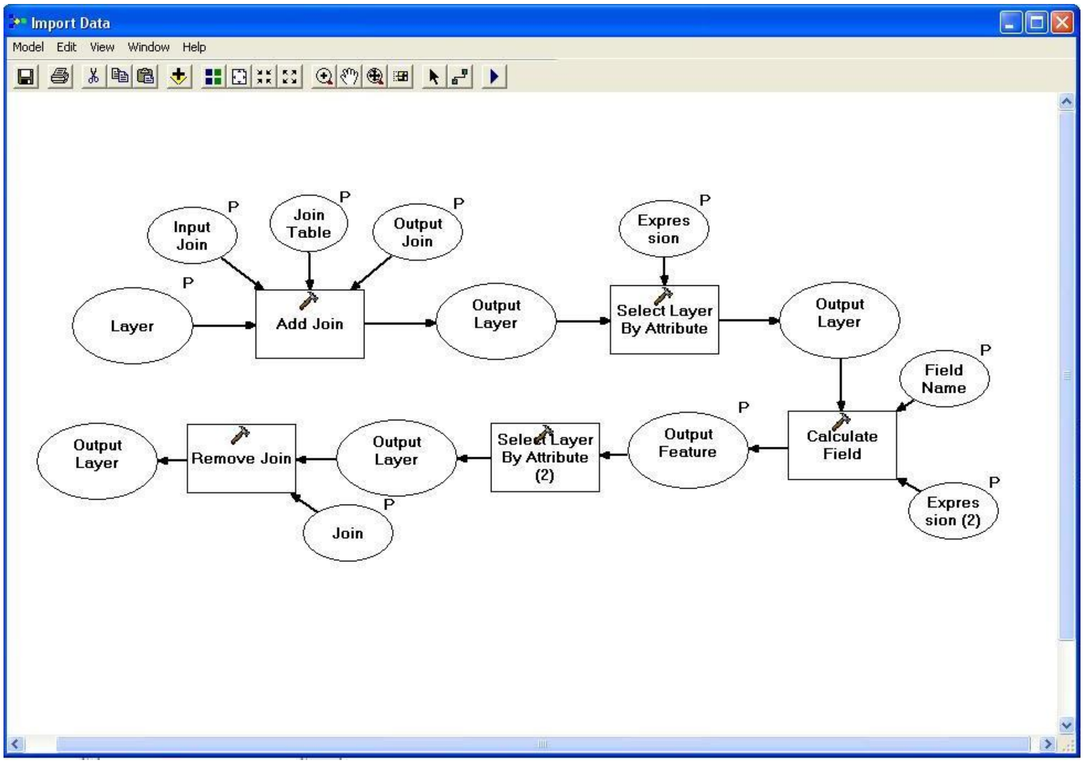


**Figure 3.7** Model diagram for “Import Data” tool

These new GIS tools are generated to perform necessary operations associated with the evaluation of environmental and economical criteria in a simple and timely manner. They ease the implementation of the proposed procedure and allow the decision makers to conduct the analysis easily.

### 3.3. Representation of Environmental Objectives and Economical Feasibility Criteria as Fuzzy Sets

The third step (see Figure 3.1) is representation of environmental objectives and economical feasibility criteria as fuzzy sets. Most decision making problems contain different types of uncertainty which may be due to several reasons, such as complexity of the problem, randomness, variability, or vagueness. The vagueness may be due to the fuzziness inherent in our natural language or incomplete information (Ross, 2005). Zadeh (1965) suggested that such uncertainty in decision making process can be dealt with fuzzy sets. Fuzzy sets may be used to represent criteria or objectives which do not have crisp boundaries usually due to availability of only incomplete information about these criteria or objectives.

Fuzzy sets which include crisp (precise) sets are characterized by membership functions. For a crisp (precise) set $A$, an element $x$ in the universe $X$ is either a member of the set $A$ or not. Mathematical function of this binary membership can be represented as (Ross, 2005):

$$X_A(x) = \begin{cases} 1, & x \in A \\ 0, & x \notin A \end{cases} \tag{1}$$

where $X_A(x)$ indicates an explicit membership of element $x$ in set $A$, and the symbol $\in$ and $\notin$ denote contained in and not contained in, respectively. However, for a fuzzy set it is not possible to talk about a zero/one (i.e. not belongs to set $A$ or belongs to set $A$) relation but rather a grade of membership. Zadeh (1965) suggested utilization of the continuous interval between zero and one rather than a binary membership in order to represent various “degrees of membership”. While zero indicates no membership, one indicates full membership similar to that of a crisp set. Thus, the nearer the value of membership to unity, the higher the grade of membership of $x$ in $A$. The difference between crisp and fuzzy sets is that an element $x$ in a set of universe can be represented by an infinite number of values between zero and one in fuzzy sets while it can only be represented by a zero or one for the crisp sets (Ross, 2005).

Representation of complex criteria using crisp sets may not always be reasonable. For example, Caliskan (2009) suggests that locations with a minimum solar radiation of 4.5 $kWh/m^2$-day are suitable for solar power plants. In evaluating the suitability of an area for a solar power plant with respect to the criteria Caliskan (2009) suggested, if a crisp set is used then all the alternative locations having a solar radiation of 4.5 $kWh/m^2$-day and higher will be appropriate and the rest of the locations will be inappropriate. However, if a degree of suitability with respect to solar radiation can be assigned, then a location with a solar radiation of 4 $kWh/m^2$-day may be classified as almost suitable and a solar radiation of 6 $kWh/m^2$-day may be classified as highly suitable for a solar power plant. Instead of defining clear boundaries (i.e. zero/one type), membership functions allow calculation of degrees of belongingness to fuzzy sets. In this thesis, environmental objectives and economical feasibility criteria are represented as fuzzy sets.

The degree of compatibility of each alternative location (i.e. grid point) with respect to each environmental objective and economical feasibility criteria is determined by using the membership functions of the fuzzy sets associated with the environmental objectives and economical feasibility criteria. The degree of compatibility is referred to as the individual satisfaction degree. Individual satisfaction degrees associated with each alternative location are then aggregated into a single value, an overall satisfaction degree by using various aggregators such as “and”, “or” and OWA.

### 3.4. Multi-criteria Decision Making (MCDM)

MCDM which is used to evaluate a set of alternatives with respect to multiple criteria is the fourth step of the procedure (see Figure 3.1). In this thesis, individual satisfaction degrees of environmental objectives or economical feasibility criteria are aggregated into a single satisfaction degree by using “and”, “or”, and OWA aggregation operators.

“And” and “or” aggregation operators are the most commonly used operators and represent “Satisfaction of all the desired criteria” and “Satisfaction of any of the desired criteria” (Yager, 1988). On the other hand, in many cases decision makers’ preferences may not be represented by the pure “and” or pure “or” operators. For such cases, Yager (1988) proposed the OWA function which corresponds to somewhere between these two extreme cases. The rationale of this application is based on aggregation by ordered position of attributes rather than classical weighted averaging. Three aggregator operators, “and”, “or” and OWA are explained in detail in the following sections.

#### 3.4.1. “And” Operator

T-norms are a way to apply “*anding*” operators for decision makers who desire satisfaction of all of the criteria. T-norm operators enable implementation of fuzzy set aggregation. It is noted by Yager (1996a) that t-norm is a way to find Pareto optimal solution because of its monotonic properties. In other words, if one of the alternatives has a zero satisfaction degree, evaluation of overall satisfaction degree returns zero. For instance, if the decision maker wants to satisfy all of the $n$ criteria, $\overline{F}_i$, $i = 1,\ldots,n$, then this can be represented by:

$$D = \overline{F_1} \cap \overline{F_2} \cap \ldots \cap \overline{F_n} \qquad (2)$$

The bar sign on capital letters is used to represent fuzzy sets.

The following theorem expresses the important property of t-norm operator: Considering $T$ corresponds to the t-norm operator, then for any $a$ and $b$: $T(a,b) \leq Min(a,b)$. Implementation of "*anding*" operators allows for no compensation for one bad satisfaction in MCDM (Yager, 1988).

### 3.4.2. "OR" Operator

T-conorms are aggregation operators which correspond to the "*oring*" operators. If decision maker requires satisfaction of any of the criteria, t-conorms can be used. For this purpose, union operator is used in order to connect the criteria as follows (Yager, 1996a):

$$D = \overline{F_1} \cup \overline{F_2} \cup \ldots \cup \overline{F}_n \tag{3}$$

The following theorem expresses the important property of t-conorm operator: Considering $S$ corresponds to the t-conorm operator; then for any $a$ and $b$: $S(a,b) \geq Max(a,b)$. Implementation of "*oring*" operators allows for no distraction from one good satisfaction in MCDM (Yager, 1988).

### 3.4.3. Ordered Weighted Averaging (OWA)

OWA aggregation concept was first suggested by Yager in 1988 (Yager, 1988). A mapping $f$ from $I^n \rightarrow I$ (where $I = [0,1]$) is called an OWA operator of dimension $n$ if associated with $f$ is a weighting vector $W = [W_1 W_2 \ldots W_n]^T$ such that

1) $W_i \in (0,1)$

2) $\sum_i W_i = 1$

where

$$f(\mu_{S,1}, \mu_{S,2}, \ldots, \mu_{S,n}) = W_1 b_1 + W_2 b_2 + \ldots + W_n b_n \tag{4}$$

where $b_i$ is the $i$th largest element of $\mu_{S,1}, \mu_{S,2}, \ldots, \mu_{S,n}$ (Yager, 1988; Yager, 1996a). The aggregation operation is represented by $f$, and the individual satisfaction of each alternative, $S$ for fuzzy objective $\overline{F_i}$ is represented by $\mu_{S,i}$. The distinction of OWA operator from other aggregation methods is based on the fact that the weights are assigned to the criteria not according to particular element, but a particular ordered position (Yager, 1988).

#### 3.4.3.1. Quantifier Guided OWA Combination

Decision makers' attitudes toward the solution may not always be like "all of the criteria must be satisfied" or "any of the criteria must be satisfied" but they may desire just some proportion of the criteria to be satisfied. For example, satisfaction of "most", "few", "at least 20 percent", and "many criteria" can be required for an acceptable solution (Yager, 1996a). Linguistic quantifiers such as "most", "many", "at least half", "some", and "few" can be implemented by mathematical tools of fuzzy set theory and this allows inclusion of decision makers' attitudes into the decision process. Mathematical expressions of the natural language can be obtained by fuzzy logic; hence, it allows us to construct multi-criteria decision functions (Yager, 1996a).

The structure of OWA operator is suitable for combining the objectives under the guidance of a quantifier. The process of determining the best location using linguistic quantifier $\overline{Q}$ is called quantifier guided aggregation. The linguistic quantities can be represented as a fuzzy set $\overline{Q}$ of the unit interval. In this representation, for each $y \in I$, $Q(y)$ indicates the degree to which the proposition $y$ satisfies the concept denoted by $\overline{Q}$ (Yager, 1996a and Yager, 1996b). The decision maker feels satisfaction of $\overline{Q}$ fuzzy objectives is necessary for a good solution.

Yager (1996b) expanded relative quantifiers by three sub-categories: (1) Regular Increasing Monotone (RIM) quantifier such as "all", "most", "many", and "at least $\alpha$", (2) Regular Decreasing Monotone (RDM) quantifier such as "at most one", "few", "at most $\alpha$", and (3) Regular UniModal (RUM) such as "about $\alpha$".

In order to obtain the overall satisfaction degree of an alternative, individual satisfaction degree with respect to each criterion need to be aggregated in a way to represent decision makers' attitude. In this study, we believe that satisfying "*most*" of the environmental objectives and economical feasibility criteria (i.e. $\overline{Q}$ represents "*most*" of the criteria) is a reasonable expectation. Thus $\overline{Q}$ is a RIM quantifier. For this purpose weights are generated as follows:

$$w_i = Q\left(\frac{i}{n}\right) - \left(\frac{i-1}{n}\right) \quad for\ i = 1,2,\ldots,n \qquad (5)$$

In this study, we assume that the guided quantifier "*most*" is defined as $Q(r) = r^2$ (Yager, 1996a and 1996b).

In order to obtain the overall satisfaction degree of an alternative, individual satisfaction degree with respect to each criterion need to be aggregated in a way to represent decision makers' attitude (Yager, 1996a, and Yager, 1996b). In this process, tradeoffs lie between the worst case scenario and best case scenario. OWA operators which can be used to state the decision makers' preferences, allow compensation between evaluation criteria according to trade offs (Malczewski, 1999).

### 3.5. Site Selection

At the end of the MCDM process, an OEPI and an overall index for renewable energy potential is calculated. Aggregation of these two criteria for each grid is another decision making process and is the fifth step of the procedure (see Figure 3.1). The proposed criteria for site selection of wind and solar energy systems are given in Table 3.2.

**Table 3.2** Site selection rules

| Degree of satisfaction for "Sufficient potential for wind energy generation" for wind energy (or OSEPI for solar energy) | Degree of satisfaction for "Satisfaction of most of the environmental objectives" (OEPI) | DECISION for the grid (i.e. alternative) |
|---|---|---|
| 0.0-0.5 | 0.0-0.5 | Eliminate – due to both insufficient potential and environmental concerns. |
| 0.0-0.5 | 0.5-1.0 | Eliminate – due to insufficient potential. |
| 0.5-1.0 | 0.0-0.5 | Eliminate for now – due to environmental concerns. Consider remedial actions and reevaluate. |
| 0.5-1.0 | 0.5-1.0 | Mark as priority site for wind or solar energy generation. |

As can be seen from Table 3.2, according to the decision rules, an OEPI and an OSEPI for solar energy (or degree of satisfaction for "Sufficient potential" for wind energy) with degrees of 0.5 and higher are required for a site to be identified as priority site for solar (or wind) energy constructions. For this purpose "and" operator is used to aggregate OEPI and OSEPI for solar energy (or degree of satisfaction for "Sufficient potential" for wind energy). This aggregation results in an OPI value for each grid and grids with an OPI of 0.5 and higher are selected as priority sites.

The final step is to identify the suitable locations where wind and solar energy constructions can be deployed together as a hybrid system (see Figure 3.1). Therefore, priority site maps of wind and solar energy (individual satisfaction degree values with 0.5 and higher) are overlaid in GIS environment using the "and" operator. This procedure is to identify suitable locations for hybrid systems.

# CHAPTER 4

# IMPLEMENTATION

## 4.1. Case Studies

Site selection procedures for solar power plants and wind turbines are developed for a selected study area within Turkey. Then using the results of these two case studies appropriate locations for hybrid systems (i.e. systems including solar and wind power plants together) are identified. The details of these three case studies are provided in this chapter.

Wind and solar potential atlases of Turkey are developed by General Directorate of Electrical Power Resources Survey and Development and are given in Figure 4.1 and Figure 4.2, respectively. These maps are used to identify economically feasible locations in terms of solar and wind energy generation. As can be seen from Figures 4.1 and 4.2, western part of Turkey has high wind and solar energy potentials which makes this location attractive for renewable energy investors. Particularly, a number of wind farm projects have been initiated in recent years and there are already 17 operating wind farms most of which are located in the western part of Turkey (Web 1).

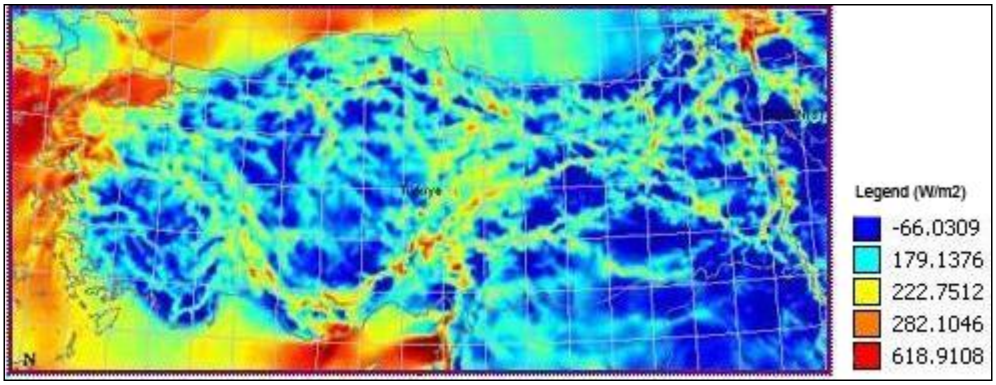


**Figure 4.1** Wind energy potential atlas of Turkey (Web 4)

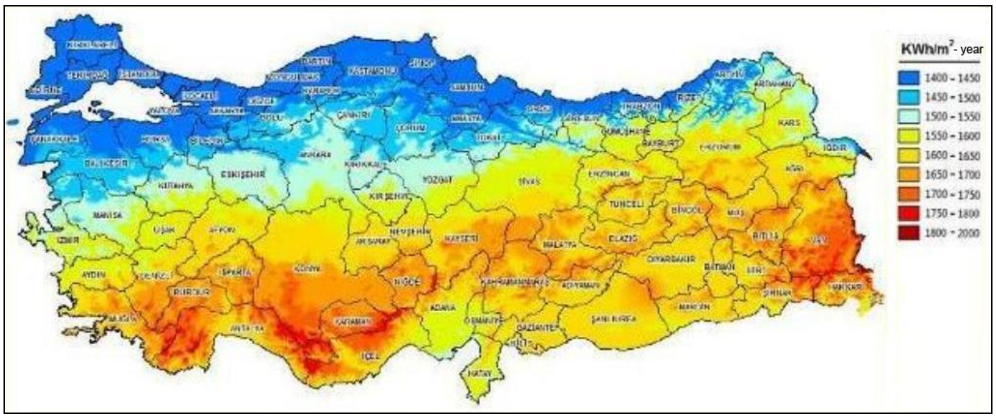


**Figure 4.2** Solar energy potential atlas of Turkey (Web 9)

In this thesis, a region including Uşak, Aydın, Denizli, Muğla, and Burdur provinces is selected as the study area due to the high wind and solar energy potentials of the region. Location of the study area within Turkey can be seen in Figure 4.3. After the study area is selected, necessary data are collected in order to identify environmentally and economically feasible locations for wind turbines and solar power plants. Required data are solar and wind energy potentials, forest areas, national parks, natural protection zones, housing areas, national electricity grids, bird migration path, airports, water bodies, wetlands, operating wind farm locations and they are shown in Figure 4.4.

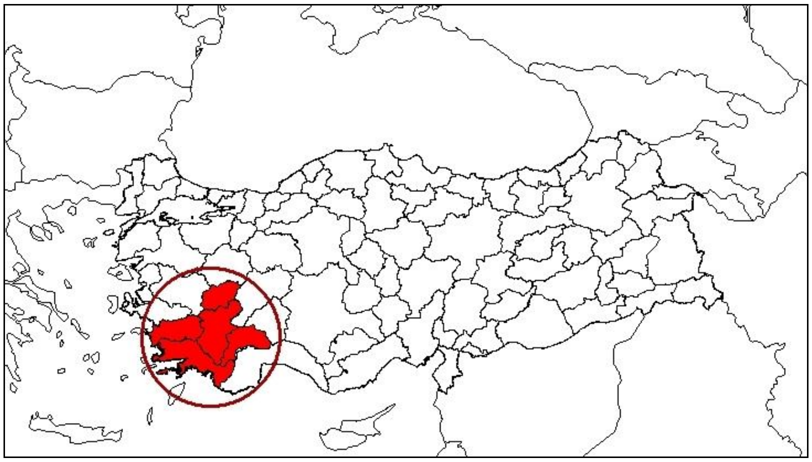

**Figure 4.3** Study Area in Turkey

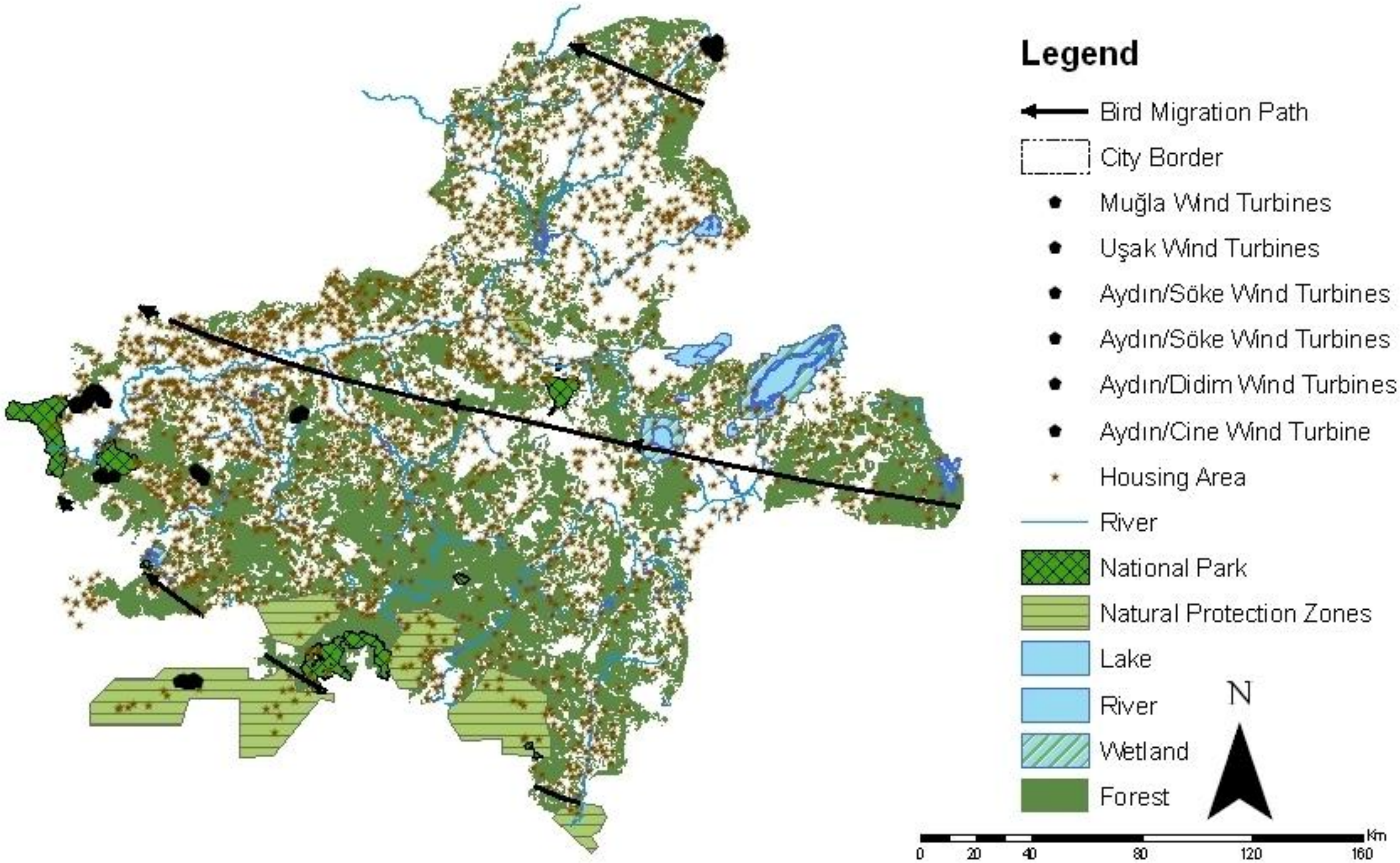


**Figure 4.4** Morphological features of the study area

### 4.2. Solar Energy

Renewable energy resources potentials should be considered together with associated environmental impacts in the future energy development plans. The aim of this study is to create a spatial decision support tool for site selection of solar power plants by using GIS tools. Indentifying the suitable locations for solar power plant installation requires comprehensive analyses. GIS can provide guidance as a spatial decision support tool for identifying environmentally and economically feasible locations. GIS tools enable a wide range of analysis of geo-referenced data, and visual presentation of cartographic maps. Each map reveals the preference of a given set of models and decision procedures (Seffino et al., 1999). In this study, several cartographic maps such as forest areas, wetlands, water bodies, electricity transmission lines, settlement areas etc. are used to produce environmental fitness and economic feasibility maps.

Decision criteria are identified with respect to environmental acceptability and solar energy potential. Environmental impacts of solar power installations are identified studying current Turkish legislations and literature, and fuzzy objectives are generated using the gathered information. Solar potential map of Turkey which was developed by the General Directorate of Electrical Power Resources Survey and Development Administration together with various other criteria such as slope of the land, proximity to transmission lines and urban areas are utilized to evaluate economical feasibility of potential locations in terms of solar energy generation. Proposed methodology is applied on a study area chosen from western part of Turkey. The study area which is composed of Uşak, Aydın, Denizli, Muğla, and Burdur provinces is divided into 250 m by 250 m grids and each grid represents an alternative location for solar power plant installations.

Fuzzy sets representing economical feasibility criteria and environmental objectives are characterized by appropriate membership functions. Individual satisfaction degrees of each environmental objective and each economical feasibility criteria for each grid are calculated separately. Then, individual satisfactions of environmental objectives and economical feasibility criteria are aggregated into an OEPI and an OSEPI, respectively. OWA operator is used for the aggregation process. In the end, a map for environmental fitness and a map for solar energy generation feasibility are developed in GIS environment. Finally, these two maps are overlaid to identify both potentially and environmentally feasible locations for solar power plant installations within the study area.

### 4.2.1. Methodology

A general flowchart for the site selection process for solar power plants, wind turbines and hybrid systems is given in Figure 3.1. The relevant parts of this flowchart for the solar power plant site selection process are given in Figure 4.5. As can be seen from Figure 4.5, the first step is the identification of environmental objectives and economical feasibility criteria. In the second step, data related with environmental objectives and economical feasibility criteria are collected and processed in GIS environment. The next step is to identify fuzzy membership functions of environmental objectives and economical feasibility criteria. The membership functions of these fuzzy sets are used to compute individual satisfaction degrees of each alternative location for each environmental objective and economical feasibility criteria. Afterwards, an OEPI and an OSEPI are calculated by aggregating individual satisfaction degrees using spatial MCDM. The final step is to overlay OEPI and OSEPI layers in GIS to identify suitable locations for solar power plants.

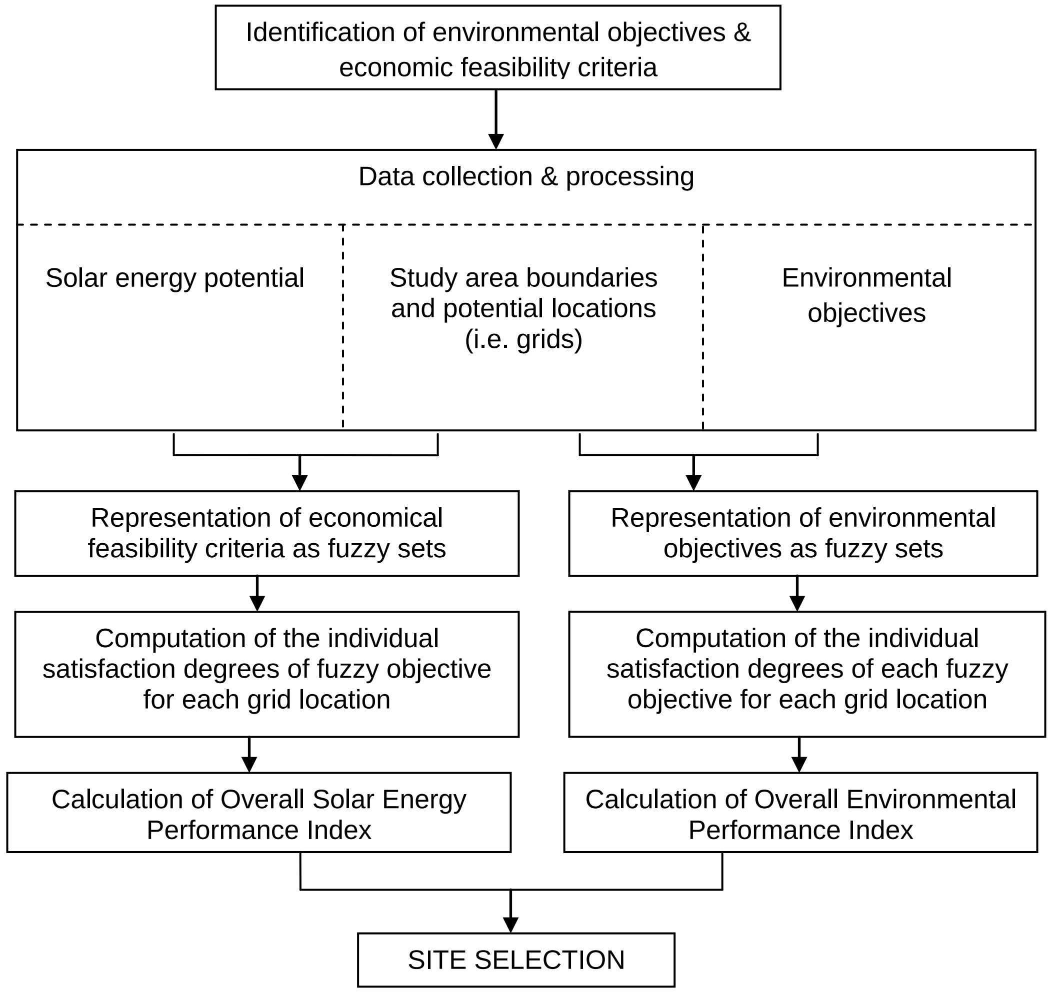


**Figure 4.5** Flowchart of site selection procedure for solar power plants

#### 4.2.1.1. Identification of Environmental Objectives and Economical Feasibility Criteria

Even though solar energy systems may provide clean and safe energy to the public and industries, similar to many other manmade projects, solar energy systems have certain impacts on the environment. Most specific environmental concern of these systems depends on dimensions (size and nature) of the projects that generally cause loss of amenity (Tsoutsos et al., 2005). Different solar energy systems have different kind of impacts on the environment. For example, PV systems do not generate any noise or chemical pollutants during utilization (Tsoutsos et al., 2005). However, other environmental concerns most of which are related to their life-cycle exist for PV systems. These concerns are air pollution generated during transport and manufacturing and waste management of PV modules after decommissioning. On the other hand, direct impacts of PV systems are related to land use, and visual impact (Tsoutsos et al., 2005).

Visual impact is highly dependent on the location (i.e. proximity to settlement areas, natural reserves, etc.) of the PV systems. If PV modules are deployed near the area of natural beauty, visual impact on this area will be inevitable (Tsoutsos et al., 2005). In addition, General Directorate of Civil Navigation in Turkey sets some restrictions around airports in order to protect the flight security, human lives, and property. Therefore, in the first 3000 m zone there should not be any structure such as hospitals, schools or common buildings that may cause reflection. Buildings that are less than 45 m height are allowed with in the second 3000 m zone (General Directorate of Civil Navigation, 2007).

Carrion et al. (2008) proposed an environmental decision support system in order to establish grid-connected PV modules. In this study, criteria are classified in four groups: environmental, orography, location, and climate. These criteria are subdivided into factors; in environmental criterion, there are two factors which are land use, and visual impact of PV modules. Land use restrictions are based on environmental protection laws. Mostly preferable locations for PV systems are fields without vegetation. Environmental protection laws in Turkey are associated with forest areas, national parks, natural protection zones, coastline and wetlands. According to the Forest Law in Turkey, any kind of construction in forest area is forbidden. However, Ministry of Forest and Environment can allow constructions for defense, infrastructure, communication, oil research, natural gas, solid waste disposal institutions, if these activities are highly necessary to build on forest areas for public interest (Law number: 6831).

Similar to forest areas, constructions at national parks are restricted by legislation in Turkey. According to National Parks Legislation, the structures which have adverse impacts on habitat cannot be built on national parks since these areas have to be preserved. Only the structures for visitors, management and research are allowed (Official journal number: 19309). In addition, national protection zones are identified with respect to Environmental Legislation and international conservation agreements in order to protect the natural assets and take precautions to decrease environmental degradation. These areas are considered ecologically sensitive and only constructions which are compatible with the nature such as restaurants, shops, maintenance and repair facilities etc. are allowed (Official journal number: 20341).

Tsoutsos et al. (2005) stated that PV systems may cause pollution in once-cultivable land and affect the soil productivity. According to Turkish Law associated with protection of cultivable lands, agricultural area must be protected in order to sustain natural functions of the land. However, if there is not any alternative location for certain facilities such as defense, oil and natural gas research, mining activities for public interest, temporary places after emerging natural disasters, agricultural lands can be used for development (Law number: 5403).

PV systems may have negative environmental impacts on the ecosystem as well. PV modules contain toxic and hazardous materials. As a result of abnormal plant operations, these toxic materials may release into the environment. These impacts can be mitigated by proper site selection. Therefore, flora and fauna on the adjacent areas need to be considered (IEA, 1998). Wetlands as well are protected by law since they have high ecological values and biodiversity. According to the Legislation of Wetlands, there must be at least 2.5 km buffer zone to protect ecological and topographic features of these areas (Official journal number: 21937).

There are further restrictions about coastal zone in Turkish Law (Law number: 3621). According to the legislation, coastal zone is divided into two zones. The first 50 m zone is allocated to green belts, and recreational areas. The second 50 m zone is for small scaled touristic places, roads, open car parks, and treatment facilities (Official journal number: 21374).

In addition to environmental restrictions, economical feasibility of solar power plants needs to be taken into account for optimal site selection. Power plants located near urban areas may prevent transmission losses, since the urban areas are the main consumption points. Therefore, proximity to national electricity grid is one of the restrictions to retain economical feasibility. Baban and Parry (2001) stated that maximum distance from national grid should be 10 km or less in order to reduce the cost. On the other hand, proximity to urban areas is required to reduce maintenance and repair costs (Carrion et al., 2008). Therefore, Carrion et al. (2008) suggested that minimum distance from urban areas should be 5 km, and maximum distance should be 10 km.

Site selection of solar power plants also depends on land slope. Carrion et al. (2008) stated that milder slopes (less than 3%) are the most suitable sites to establish grid connected PV power plants. In addition, Hang et al. (2008) investigated the site selection factors related with solar power plants and concluded that an overall slope of less than 1% is suitable for solar power plants, and slope percentage up to 3% is acceptable, but 3% slope may increase the cost.

#### 4.2.1.2. Quantification of Objectives

Environmental objectives with respect to solar energy generation are identified through a detailed review of the literature and studying governmental laws and regulations. In this study, Turkish legislations about natural reserves (national parks, natural protection zones, forests, wetlands, and coastline) and airport construction are used in identifying environmental objectives of solar energy generation. These objectives and associated criteria are given in Table 4.1.

**Table 4.1** Environmental objectives and associated criteria from regulations and previous studies

| Environmental objectives | Criteria | Reference |
|---|---|---|
| Acceptable in terms of natural reserves | Only the constructions for public interest are allowed if activities are highly necessary to build on forest areas | Law number: 6831 |
| | Only the constructions which are compatible with the nature are allowed | Official journal number: 20341 |
| | The structures which have adverse impacts on habitat cannot be built | Official journal number: 19309 |
| Acceptable in terms of agricultural areas | Agricultural area must be protected in order to sustain natural functions of the land | Law number: 5403 |
| | Cultivable land might be damaged by large scale installations | Tsoutsos et al., 2005 |
| Acceptable in terms of lakes and wetlands | At least 2.5 km buffer zone to protect ecologic and topographic features | Official journal number: 21937 |
| Acceptable in terms of coastline | Minimum distance is 100 m from the coastline | Official journal number: 21374 |
| Acceptable in terms of flight security | Minimum distance to airports is 3000 m and maximum distance to airports is 6000 m | General Directorate of Civil Navigation, 2007 |

In addition to environmental objectives various criteria to evaluate economical feasibility of an alternative location is considered in the site selection process. Here, economical feasibility is used to represent suitability of each alternative location for solar power plants with respect to solar energy potential, economical and physical aspects. Therefore, as can be seen from Table 4.2, sufficient potential for solar energy generation, acceptable slope, acceptable proximity to transmission lines, acceptable proximity to urban areas are identified as economical feasibility criteria. These criteria are identified by using previous studies and interviews with the General Directorate of Electrical Power Resources Survey and Development Administration.

**Table 4.2** Economical feasibility criteria and associated criteria from interviews and previous studies

| Economical Feasibility Criteria | Criteria | Reference |
|---|---|---|
| Sufficient Potential for Solar Energy Generation | Min solar radiation value is 4.5 $kWh/m^2$-day | Caliskan, 2009 |
| Acceptable slope | Slope up to 3%, 1% most economical | Hang et al., 2008 |
| | Less than 3% | Carrion et al., 2008 |
| Acceptable proximity to transmission lines | Not be located further than 10 km from national grid | Baban and Parry, 2000 |
| Acceptable proximity to urban areas | Min distance to urban areas should be 5 km. Max distance to urban areas should be 10 km. | Carrion et al., 2008 |
| | Electrical production plants need to be located near urban area to avoid transmission loss | |
| | Proper site selection and design of large PV installations due to the visual impact | Tsoutsos et al., 2005 |

#### 4.2.1.3. Data Collection and Processing

Data processing is done in GIS environment. To calculate individual satisfaction degrees of environmental objectives and economical feasibility criteria for each alternative location (i.e. grip point), several GIS map layers need to be prepared. These layers include the boundaries of the study area, solar energy potential, settlement areas, water bodies, natural reserves, coastal boundaries, slope, transmission lines etc. Then, study area is divided into 250 m by 250 m grids. Each grid represents an alternative location for installation of solar power plants. As a final step, criterion maps with respect to each environmental objective and economical feasibility criteria are generated. For example, for “Acceptable in terms of lake and wetland” environmental objective, nearest distances to lakes and wetlands are calculated for each alternative location (i.e. grid point).

#### 4.2.1.4. Representation of Environmental Objectives as Fuzzy Sets

Five environmental objectives considered and related criteria for these objectives are given in Table 4.1. Solar power plants require large areas for installations. For example, a solar power plant in Portugal which is located 200 km southeast of Lisbon has 52000 solar panels covering about 60 ha (Web 10). A PV system which is located at the northeast of Las Vegas, USA has 72000 solar panels that covers an area of 140 acres (approximately 57 ha) (Web 11). Thus installation of solar power plants results in clearing of large areas. This fact makes installation of solar power plants unsuitable on agricultural land, forest areas, natural parks or preserves.

In this study, forest areas, national parks, and natural protection zones are referred to as natural preserves. As can be seen from Table 4.1, related Turkish laws and legislations have restrictions about constructions at these areas. For example, according to national parks legislation, the structures which have adverse impacts on habitat cannot be built on national parks since these areas have to be preserved. Only the structures for visitors, management and research are allowed (Official journal number: 19309).

Similarly, partial or full destruction of forest areas is forbidden by law. However, Ministry of Environment and Forestry may allow constructions related with defense, infrastructure, communication, oil research, natural gas, solid waste disposal if these activities are highly necessary to be build on forest areas (Law number: 6831). Therefore, in this study natural preserves are considered to be unsuitable for solar power plants. Since construction within these areas is forbidden by law in Turkey, instead of a fuzzy objective a crisp one is implemented for natural preserves: “It is not appropriate to construct solar power plants inside natural preserves”. In other words, a buffer zone in which acceptability of construction increases from zero to one is not used. One other reason for not using a fuzzy objective is the computational burden. Since the selected study area includes many natural preserves calculating distances for each grid point from the closest natural preserve requires a lot of time. Thus, for the sake of simplicity natural preserves are excluded from potential areas on which solar power plants may be constructed.

Another environmental objective is to protect agricultural areas. Satisfaction of this environmental objective is evaluated by using the fuzzy set called “Acceptable in terms of agricultural areas”. Tsoutsos et al. (2005) stated that large scale installations of PV systems might damage the cultivable lands. Moreover, according to Soil Protection and Land Use Law agricultural lands cannot be used without meeting agricultural purposes (Law number: 5403). Ministry of Agriculture and Rural Affairs can allow constructions related with defense, oil and natural gas research, mining activities, temporary places after emerging natural disasters, if constructions of these facilities are highly necessary. Since a numerical value is not suggested either in related laws or literature a buffer zone of 1 km is selected for agricultural areas. This indicates that acceptability of solar power plants within 1 km buffer zone around agricultural areas increases from zero to one as shown in Figure 4.6.

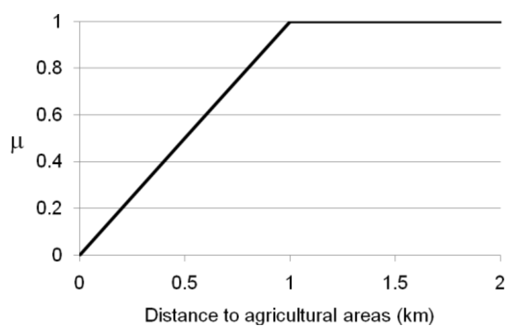


**Figure 4.6** Fuzzy set for “Acceptable in terms of agricultural areas”

As mentioned before, PV modules contain toxic and hazardous materials. As a result of abnormal plant operations, these toxic materials may be released to the environment (IEA, 1998). Besides, Turkish legislation of wetland protection has some restrictions about the constructions around the wetland areas (Table 4.1). According to this legislation, there must be at least 2.5 km buffer zone to protect ecological and topographic features of these areas. Therefore, another environmental objective used in this study is to protect lakes and wetlands. A fuzzy set called “Acceptable in terms of lakes and wetlands” is generated to evaluate satisfaction of this objective and the corresponding membership function is given in Figure 4.7.

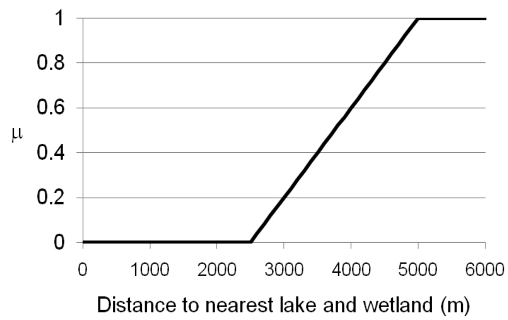


**Figure 4.7** Fuzzy set for “Acceptable in terms of lakes and wetlands”

In addition to wetlands and lakes, protection of coastal zones and rivers are considered in this study as well since energy constructions can cause water contamination, and constructions on coastal zone are restricted by Turkish Legislation of Coastline. According to the legislation, coastal zone is determined by governorship and divided into two zones. The first 50 m zone is allocated as a green belt, and can be utilized for recreational purposes only. The second 50 m zone is for small scaled touristic places, roads, open car parks, and treatment facilities (Official journal number: 21374). A fuzzy set referred to as “Acceptable in terms of coastline and rivers” is used to evaluate satisfaction of this environmental objective and associated membership function is given in Figure 4.8.

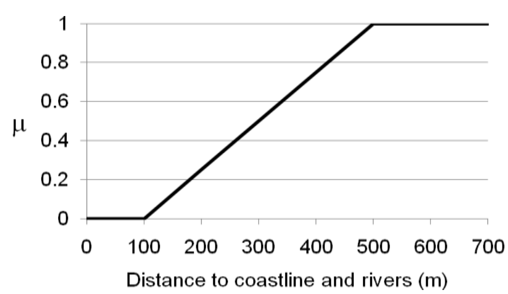


**Figure 4.8** Fuzzy set for “Acceptable in terms of coastline and rivers”

Another environmental objective is related with flight security. Since humans are a part of the environment this objective is considered under environmental objectives rather than economical feasibility criteria. A fuzzy set referred to as “Acceptable in terms of flight security” is formed to evaluate satisfaction of this objective. As can be seen from Table 4.1, according to the notice of General Directorate of Civil Navigation, structures which may shine are not allowed in the first 3000 m zone, while buildings which are less than 45 m height are allowed in the second 3000 m zone (General Directorate of Civil Navigation, 2007). According to these criteria, the membership function for the fuzzy set “Acceptable in terms of flight security” is generated and given in Figure 4.9.

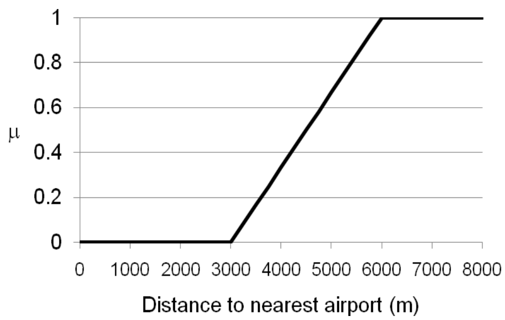


**Figure 4.9** Fuzzy set for “Acceptable in terms of flight security”

#### 4.2.1.5. Computation of Individual Satisfaction Degrees

Fuzzy membership functions associated with each environmental objective are used to evaluate individual satisfaction degrees of each alternative location (i.e. grid point) with respect to these objectives in GIS environment. Separate layers for each environmental objective are created in GIS environment and related information is stored in various databases. For example, in the layer corresponding to “Acceptable in terms of flight security”, distances between each grid point and the nearest airport is stored. These distances are used to evaluate individual satisfaction of each grid point with respect to the environmental objective “Acceptable in terms of flight security” by using the membership function given in Figure 4.9. A similar procedure is employed to calculate individual satisfaction degrees of each grid point for all the environmental objectives. Then these individual satisfaction degrees are aggregated into an OEPI. At the end of this procedure an OEPI is calculated for each grid point.

#### 4.2.1.6. Representation of Economical Feasibility Criteria Using Fuzzy Sets

In order to perform site selection of solar energy investments, both economical feasibility and environmental suitability need to be considered. Even though a location has high environmental acceptability, if the solar energy potential is not sufficient, a solar energy power plant will not be feasible at that location. Therefore, the next step is to generate the OSEPI of the study area.

For this purpose several economical feasibility criteria are identified through previous studies and personal interviews with personnel from General Directorate of Electrical Power Resources Survey and Development Administration. Economical considerations and associated economical feasibility criteria are given in Table 4.2.

During the interviews with the General Directorate of Electrical Power Resources Survey and Development Administration, it became clear that economically feasible solar radiation value for solar energy generation starts around 4.5 kWh/m$^2$-day (Caliskan, 2009). In addition, Environmental Protection Agency of USA conducted an analysis about solar energy generation potential for PV systems. In this analysis, solar radiation values between 5 – 6 kWh/m$^2$-day are classified as “very good” for energy generation from PV systems (Web 12). Economical feasibility criteria related with solar potential is represented by a fuzzy set called “Sufficient potential for solar energy generation” and its membership function is formed by using the criteria provided in Table 4.2. The membership function for “Sufficient potential for solar energy generation” is given in Figure 4.10.

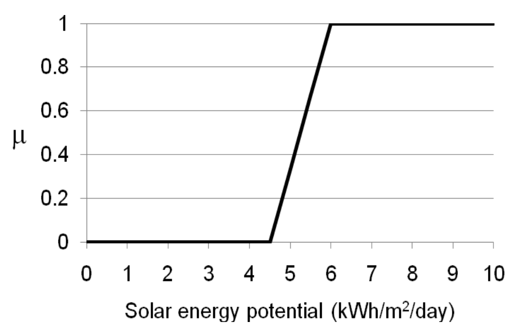


**Figure 4.10** Fuzzy set for “Sufficient potential for solar energy generation”

Land slope is another concern for the site selection of solar power plants. Criteria related with suitable land slope for solar power plant installations given in Table 4.2 are used to generate a fuzzy set called “Acceptable in terms of slope” and the membership function of this fuzzy set is given in Figure 4.11.

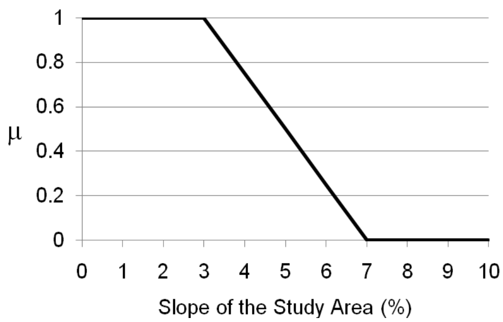


**Figure 4.11** Fuzzy set for “Acceptable in terms of slope”

Another economical feasibility criterion has been identified as the proximity to electricity transmission lines. According to Hang et al. (2008) since the transmission lines can elevate the cost, easy access to transmission lines is important for site selection. On the other hand, Baban and Parry (2001) studied the same selection problem and stated that cost factor can be tolerated up to 10 km. A fuzzy set called “Acceptable in terms of transmission lines” is generated to represent this objective. Distances less than 10 km are considered to be fully acceptable in terms of proximity to transmission lines as can be seen from Figure 4.12. The maximum distance is determined specifically for the selected study area. All the grid locations within the study area are less than approximately 45 km to the nearest transmission line. Since all grid points need to receive electricity, a location specific maximum distance is implemented for this fuzzy objective.

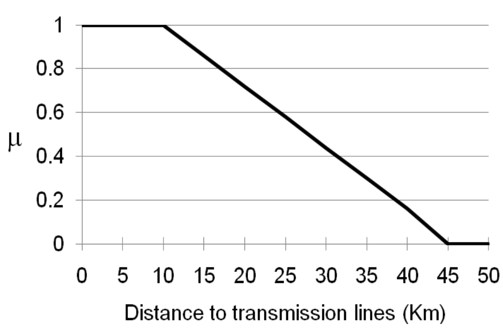


**Figure 4.12** Fuzzy set for “Acceptable in terms of transmission lines”

Proximity to urban areas is the last economical feasibility criteria. If the solar power plant is located away from urban areas, that may cause higher electricity transmission losses. Therefore power plants for electricity generation which are located near urban areas are preferable. On the other hand since solar power plants require large areas for installation in addition to various economical considerations (i.e. may be more beneficial to use land close to the urban areas for other purposes) and visual impacts, it may be preferable not to have these installations too close to the urban areas. A fuzzy set called "Acceptable in terms of proximity to urban area" is formed using these criteria and the corresponding membership function is given in Figure 4.13.


**Figure 4.13** Fuzzy set for "Acceptable in terms of proximity to urban area"

The fuzzy sets generated for the environmental objectives and the economical feasibility criteria are used to evaluate individual satisfaction degree of each alternative location (i.e. grid point) with respect to these objectives and criteria.

#### 4.2.1.7. Computation of Individual Satisfaction Degrees

Membership functions associated with environmental objectives and economical feasibility criteria are used to compute individual satisfaction degrees of each alternative location (i.e. grid point) in GIS environment. Individual satisfaction degrees are calculated by using the previously stored data in the related layers. These individual satisfaction degrees are recorded in a separate column in the GIS database. The next step is to aggregate these individual satisfaction degrees into an OEPI and OSEPI using MCDM.

#### 4.2.1.8. Multi-criteria Decision Making (MCDM)

MCDM allows evaluation of a set of alternatives with respect to conflicting and incommensurate criteria. A criterion is a generic term that includes both the concepts of attribute and objective (Malczewski, 1999). When the standardizations of criteria are represented by fuzzy measures, MCDM concerns the aggregation of multiple fuzzy measures into a single statement which corresponds to the final degree of suitability (Jiang and Eastman, 2000). In this study, the OEPI and OSEPI are the final degrees of suitability. The combination approach is an important decision rule. In this study the OEPI and OSEPI are calculated by using the OWA aggregation operator for "satisfaction of most of the objectives". To evaluate "Satisfaction of most of the objectives" quantifier guided aggregation is used.

#### 4.2.1.9. Site Selection

At the end of the aggregation procedure, an OEPI representing "Satisfaction of most of the environmental objectives" and an OSEPI representing "Satisfaction of most of the economical feasibility criteria" for each alternative location (i.e. grid point) is calculated. Suitability of each grid for solar power plant installations needs to be evaluated based on these two criteria. Such an evaluation requires another decision making process which combines OEPI and OSEPI into a single representative value (i.e. overall performance index, OPI) for solar power plant installations. The proposed decision criteria for site selection of solar energy systems are given in Table 4.3.

**Table 4.3** Site selection criteria for solar energy systems

| OSEPI | OEPI | DECISION for the grid (i.e. alternative) |
|---|---|---|
| 0.0-0.5 | 0.0-0.5 | Eliminate – due to both insufficient potential and environmental concerns. |
| 0.0-0.5 | 0.5-1.0 | Eliminate – due to insufficient potential. |
| 0.5-1.0 | 0.0-0.5 | Eliminate for now – due to environmental concerns. Consider remedial actions and reevaluate. |
| 0.5-1.0 | 0.5-1.0 | Mark as priority site for solar energy generation. |

As can be seen from Table 4.3, alternative locations which have at least 0.5 satisfaction degrees for both OEPI and OSEPI are identified as suitable locations for solar power plant installations. These alternative locations can be referred to as “priority sites” for solar energy generation. In order to obtain priority sites, OEPI and OSEPI are overlaid using the “and” operator in GIS environment. At the end of this procedure, OPI for solar energy is acquired and grids with an OPI of 0.5 and higher are selected as “priority sites”.

### 4.2.2. Example Application for Solar Power Plants

The site selection methodology for solar energy generation is applied for a study area located in the western part of Turkey. The study area is composed of Aydın, Uşak, Denizli, and Muğla provinces. The current solar potential map of the study area is obtained from General Directorate of Electrical Power Resources Survey and Development Administration and is given in Figure 4.14. Solar energy potential map contains radiation values.

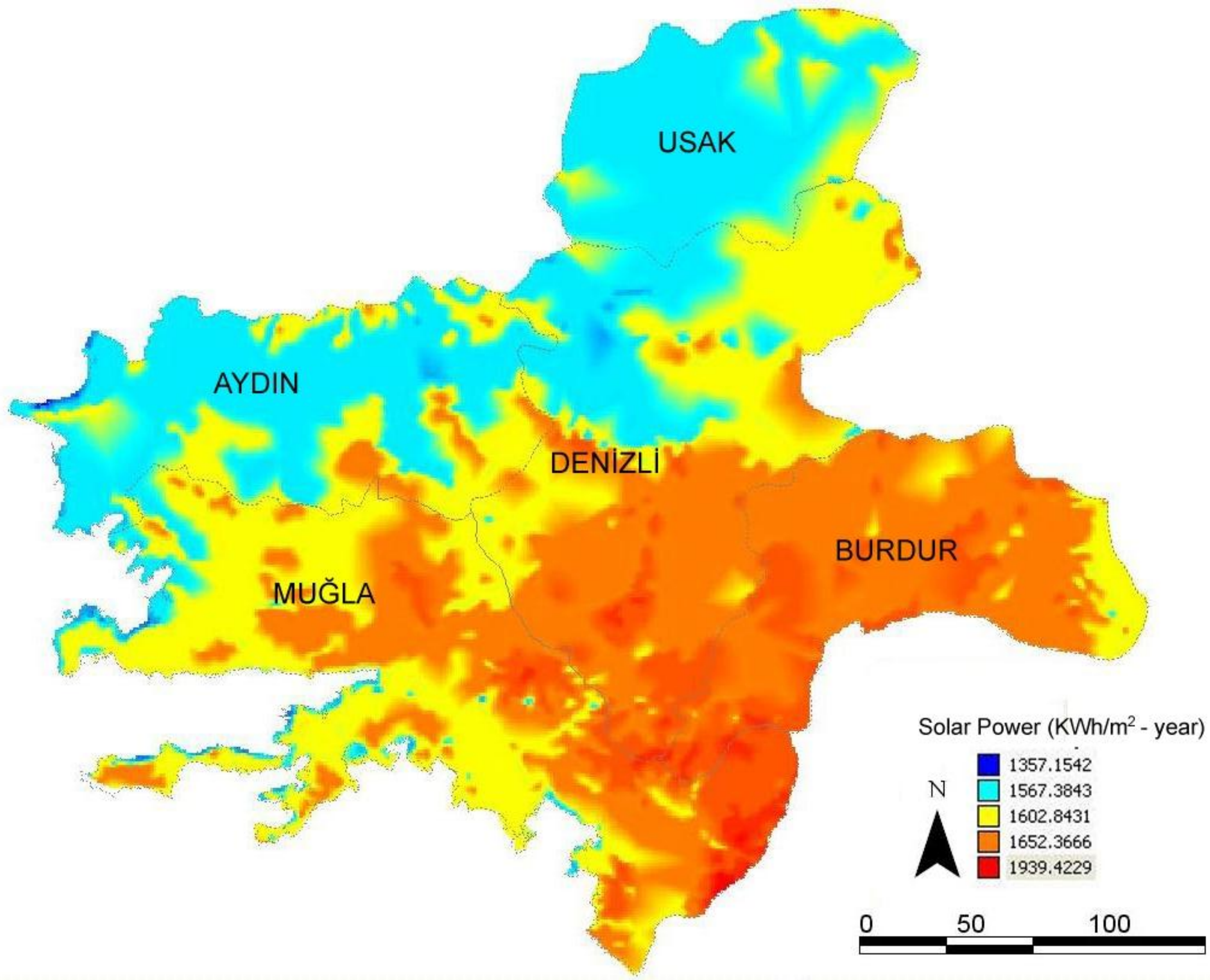


**Figure 4.14** Current solar potential for the study area

First, related layers are obtained for the study area. These layers are solar energy potential, wetlands, water bodies, natural reserves, airports, electricity transmission lines, slope, rivers and coastline. Then whole study area is converted to 250 m point grids in ArcGIS 9.2 software. Each point represents an alternative location for the solar power plant installation. Individual satisfaction degrees of environmental objectives and economical feasibility criteria for each alternative are calculated using the membership functions generated for associated criteria as given in Figures 4.6 to 4.13.

As mentioned before, one of the environmental objectives is related with protection of natural preserves. In this study natural preserves are considered to be unsuitable for solar power plants. Figure 4.15 demonstrates suitable locations for “Acceptable in terms of natural reserves”.

Fuzzy set for “Acceptable in terms of agricultural areas” is identified (see Figure 4.6), nearest distances between the centers of each grid point to the closest agricultural area are calculated and stored in the database. Individual satisfaction degree of each grid point is calculated using the nearest distances and Figure 4.6. A new column is created to store individual satisfaction degrees. Then these points are converted to raster data in order to demonstrate suitable locations for “Acceptable in terms of agricultural areas” which is given in Figure 4.16.

Protection of lakes and wetlands is another environmental objective in this study. A fuzzy set called “Acceptable in terms of lakes and wetlands” is generated and can be seen in Figure 4.7. Individual satisfaction degree for each grid point with respect to “Acceptable in terms of lakes and wetlands” fuzzy objective is calculated in the same way used for “Acceptable in terms of agricultural areas” fuzzy objective. Suitable locations for “Acceptable in terms of lakes and wetlands” are given in Figure 4.17.

In addition, protection of coastal zones and rivers is considered as one of the environmental objectives in this study and fuzzy set for “Acceptable in terms of coastline and rivers” is given in Figure 4.8. Figure 4.18 demonstrates the suitable locations for “Acceptable in terms of rivers and coastline and rivers” within the study area.

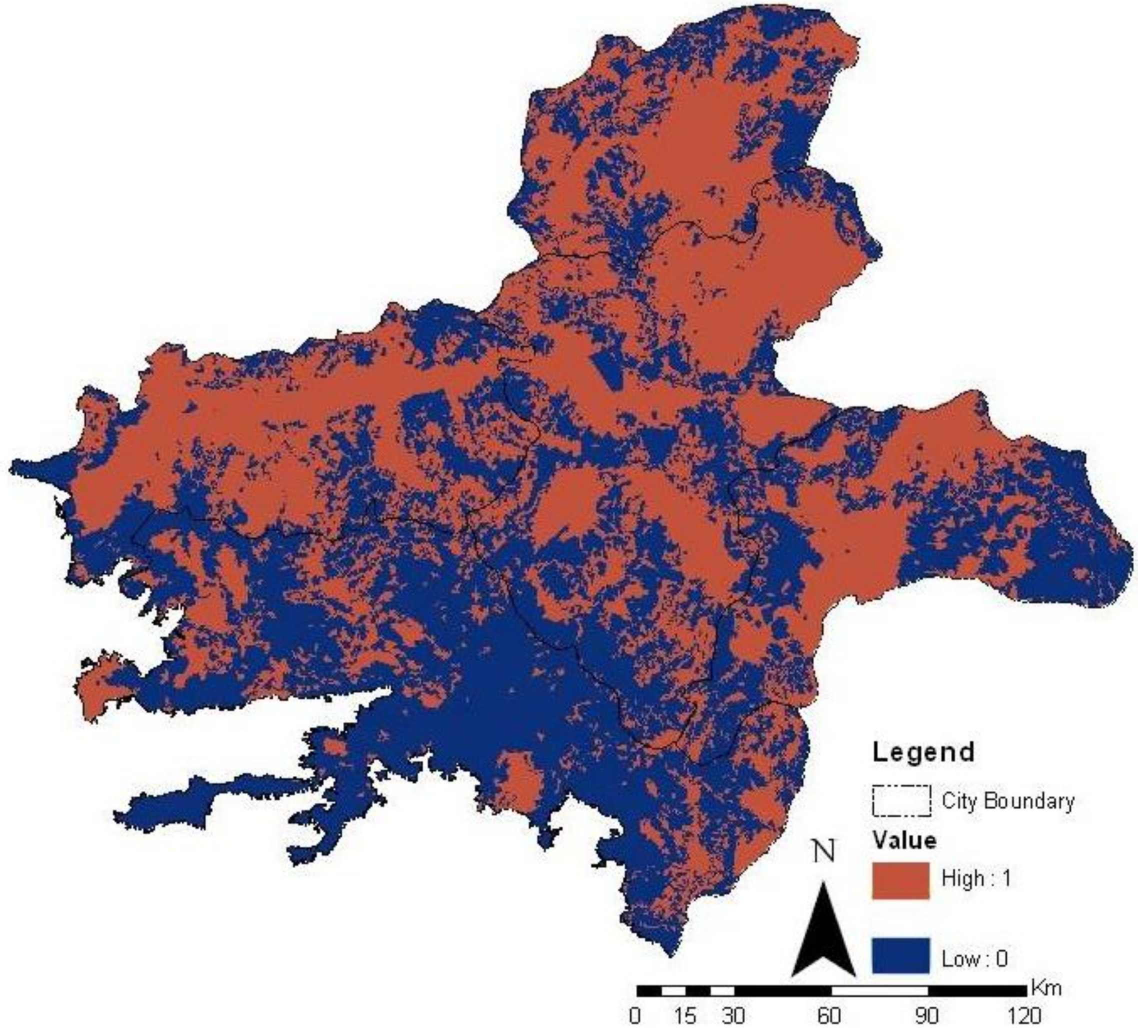


**Figure 4.15** Suitable locations for “Acceptable in terms of natural reserves”

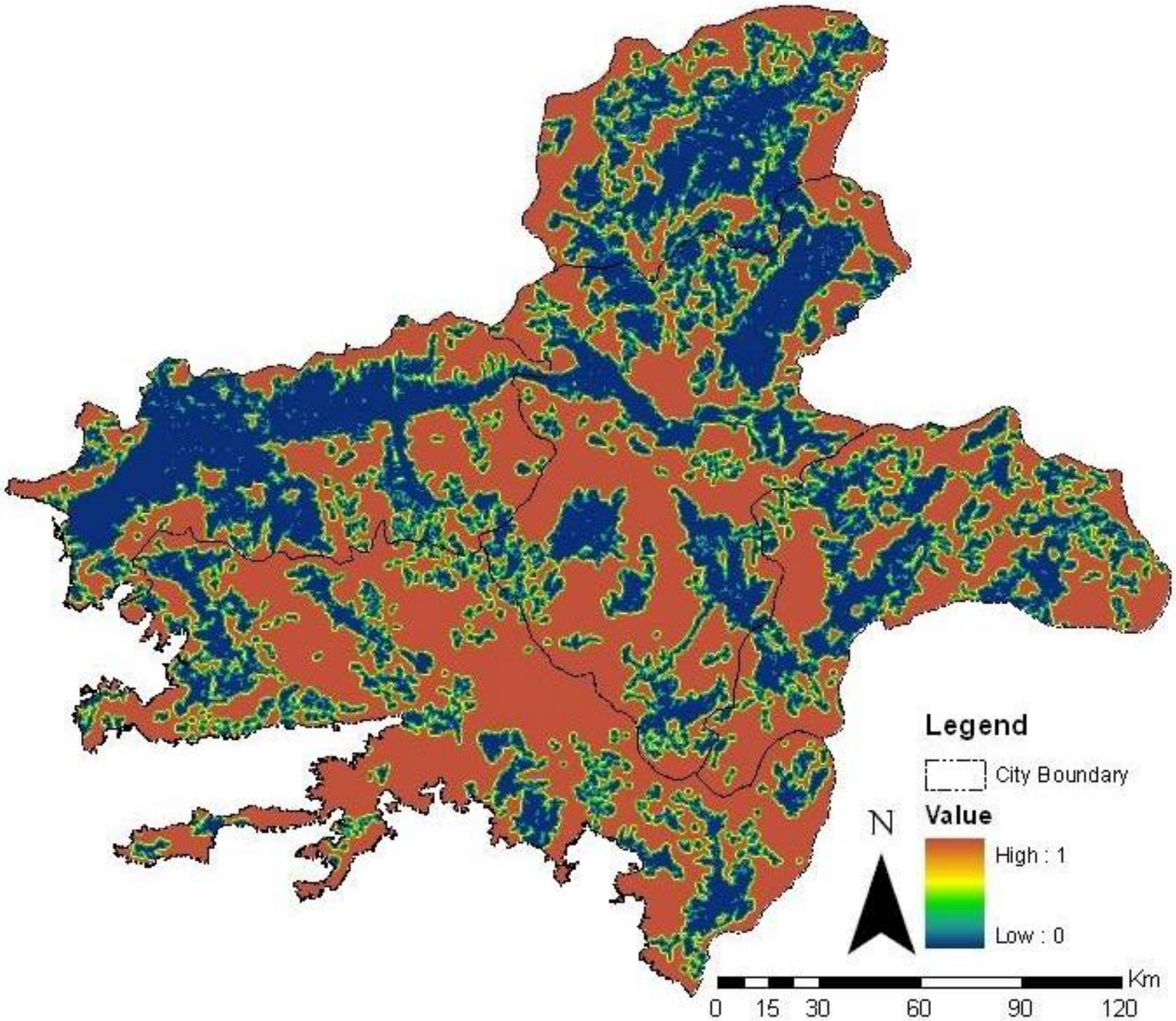


**Figure 4.16** Suitable locations for “Acceptable in terms of agricultural areas”

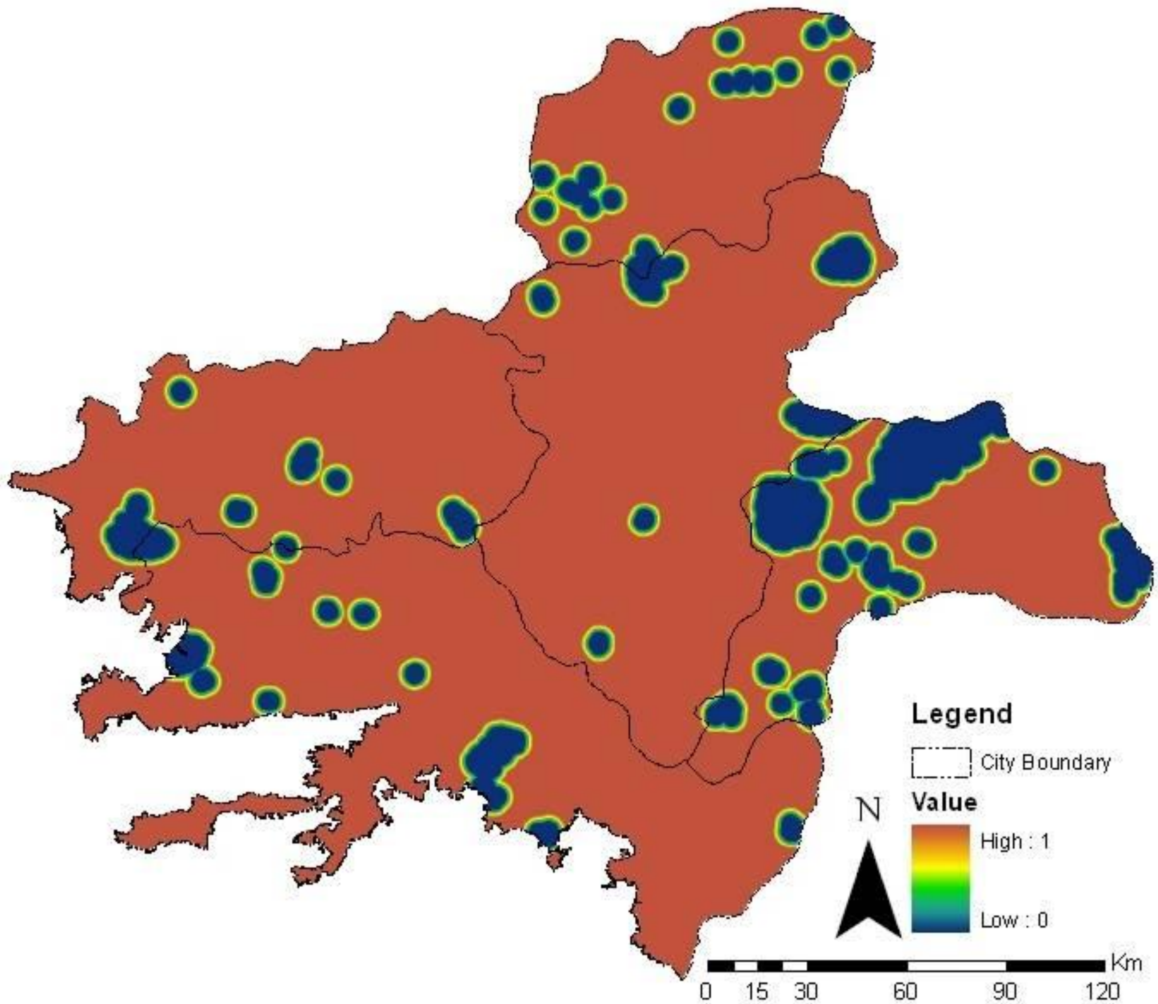


**Figure 4.17** Suitable locations for “Acceptable in terms of lakes and wetlands”

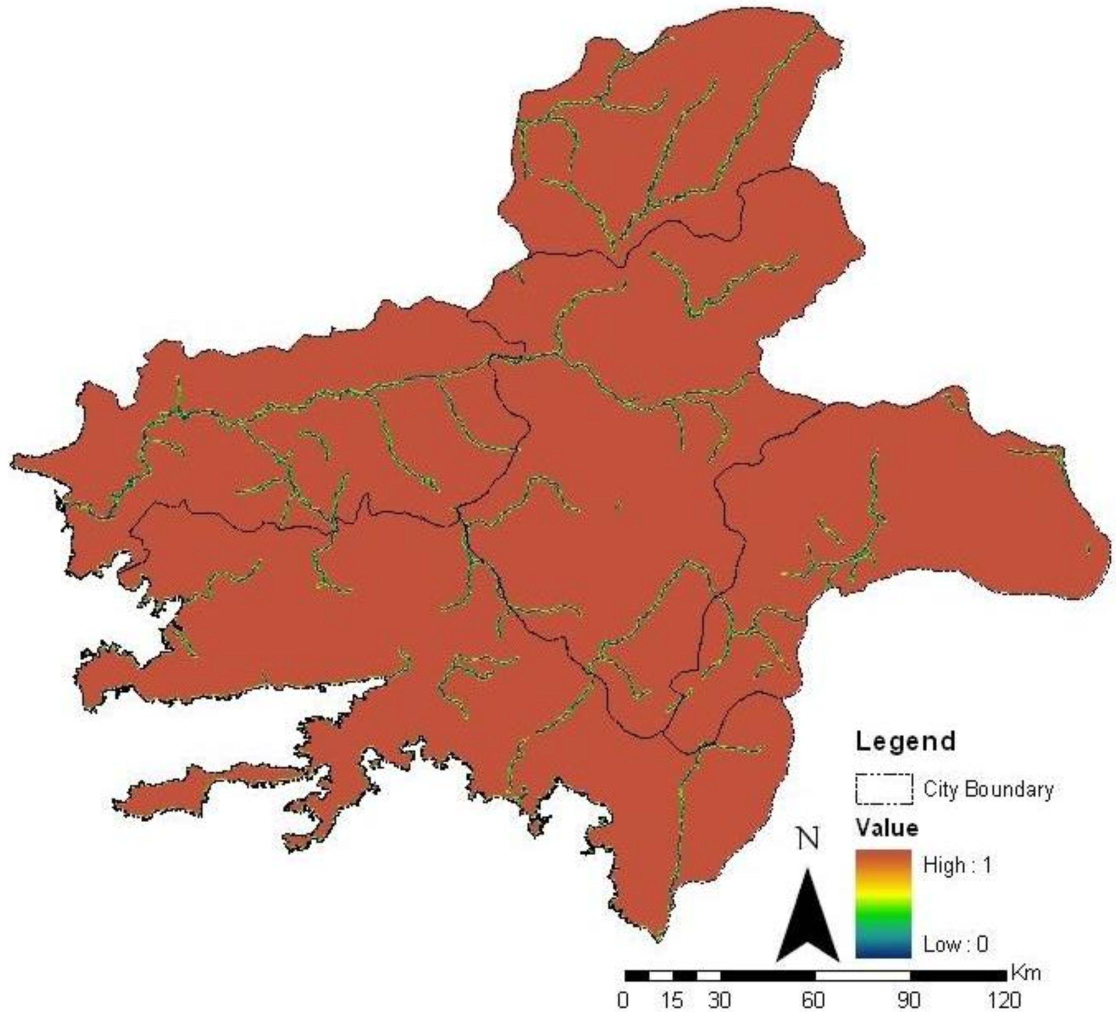


**Figure 4.18** Suitable locations for “Acceptable in terms of coastline and rivers”

Last environmental objective is related with the flight security. The membership function for the fuzzy set “Acceptable in terms of flight security” is given in Figure 4.9. In order to illustrate the fuzzy set “Acceptable in terms of flight security”, fuzzy measures of each alternative location are converted to raster data and given in Figure 4.19.

In addition to environmental objectives, economical feasibility criteria of solar energy generation are also considered in this study and given in Table 4.2. One of the economical feasibility criteria is related with solar energy potential which is represented by a fuzzy set called “Sufficient potential for solar energy generation”. The membership function for “Sufficient potential for solar energy generation” is given in Figure 4.10. In addition, Figure 4.20 illustrates the result of “Sufficient potential for solar energy generation” fuzzy set.

Land slope is another economical feasibility criterion. Therefore, a fuzzy set called “Acceptable in terms of slope” is identified and the membership function of this fuzzy set is given in Figure 4.11. In addition, suitable locations for “Acceptable in terms of slope” fuzzy set can be seen in Figure 4.21.

As mentioned before, proximity to electricity transmission lines is another economical criterion which can increase the cost. Thus, a fuzzy set called “Acceptable in terms of transmission lines” is generated and the membership function of this fuzzy set is given in Figure 4.12. In addition, Figure 4.22 demonstrates the “Acceptable in terms of transmission lines” fuzzy set within the study area. As can be seen in Figure 4.22, all of grid values have satisfaction degree which is higher than zero. Since the maximum distance in this fuzzy set is derived from the case study.

Proximity to urban areas is the last economical feasibility criteria. A fuzzy set called “Acceptable in terms of proximity to urban area” is formed using the criteria which are given in Table 4.2 and the corresponding membership function is given in Figure 4.13. In addition, Figure 4.23 illustrates the result of “Acceptable in terms of proximity to urban area” fuzzy set.

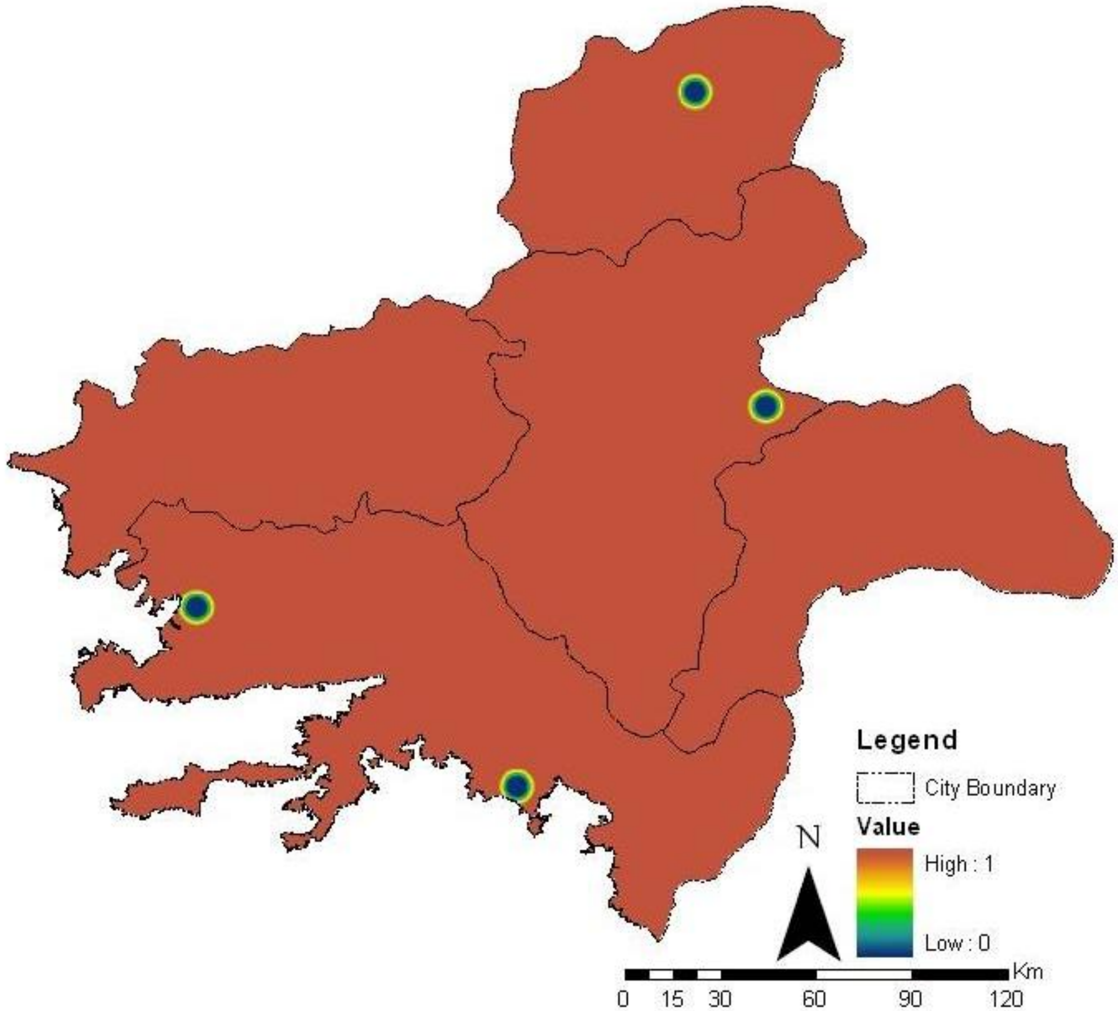


**Figure 4.19** Suitable locations for “Acceptable in terms of flight security”

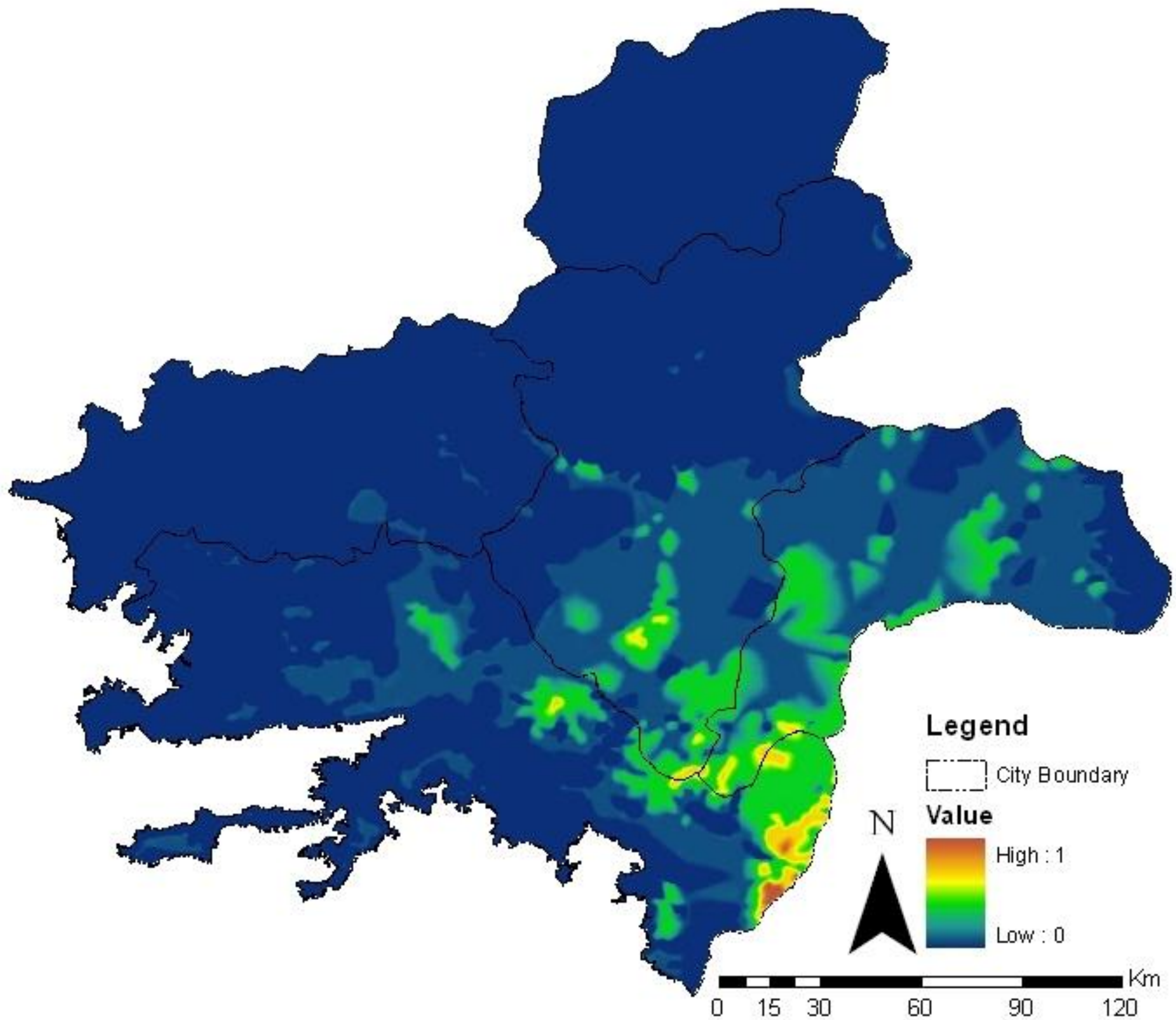


**Figure 4.20** Suitable locations for “Sufficient potential for solar energy generation”

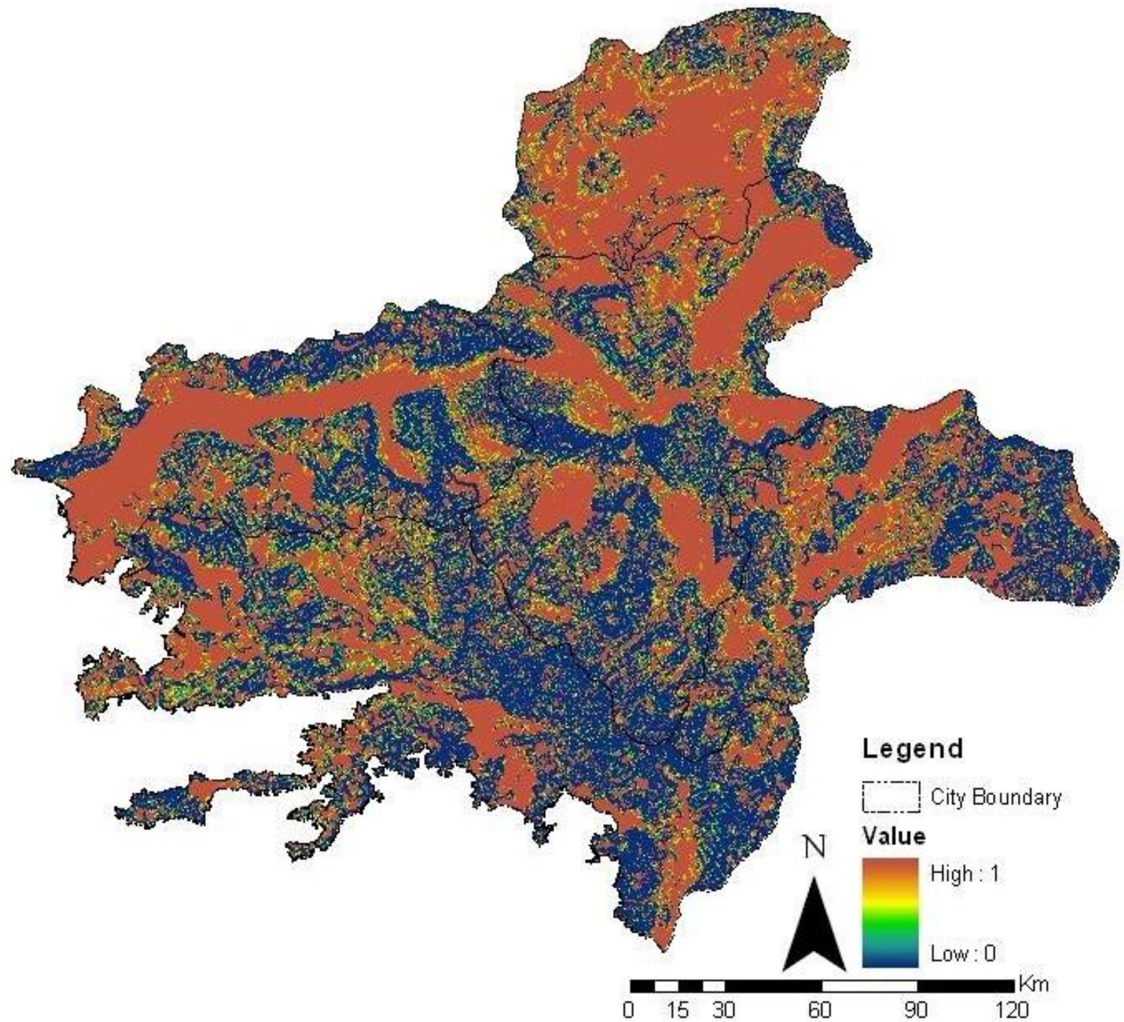


**Figure 4.21** Suitable locations for “Acceptable in terms of slope”

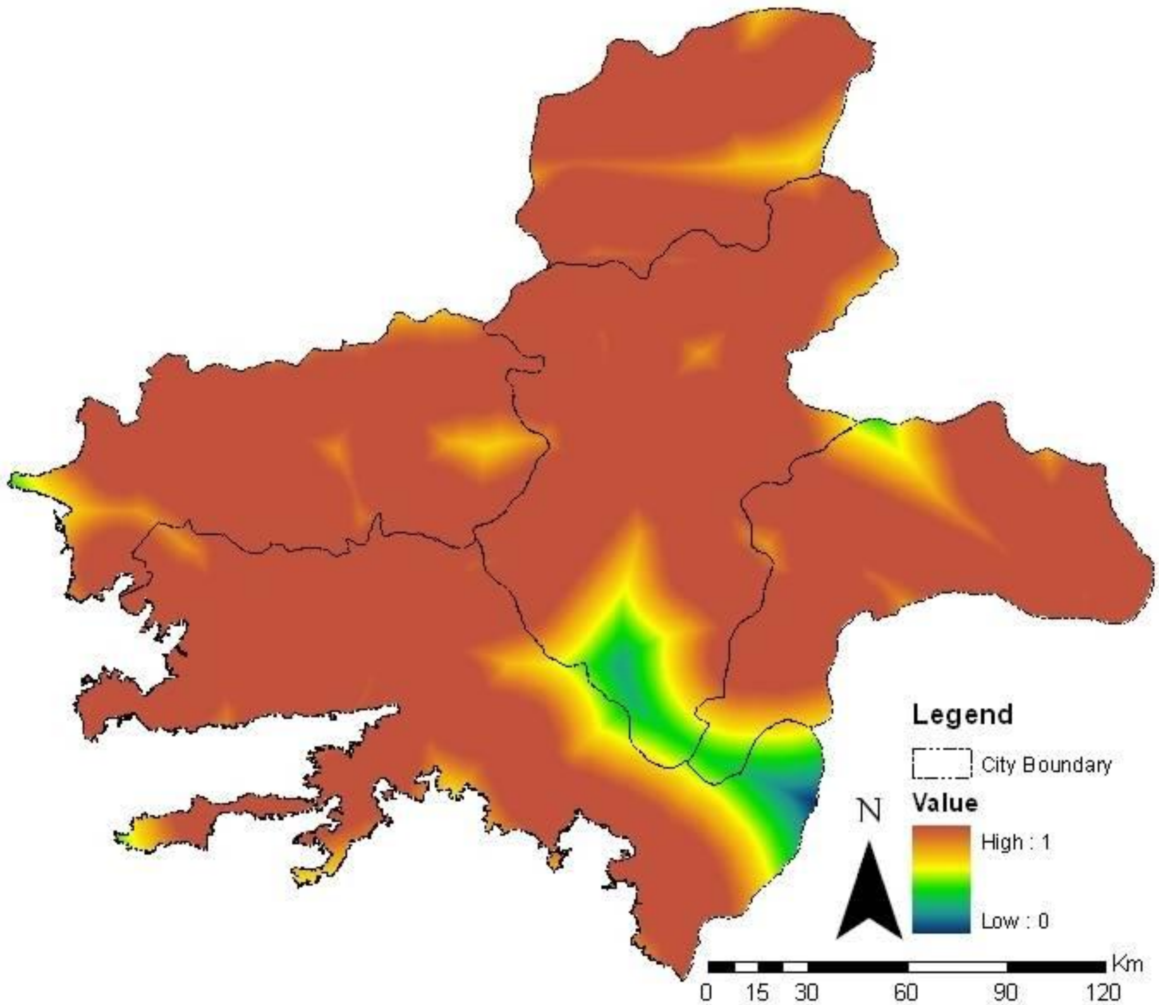


**Figure 4.22** Suitable locations for “Acceptable in terms of transmission lines”

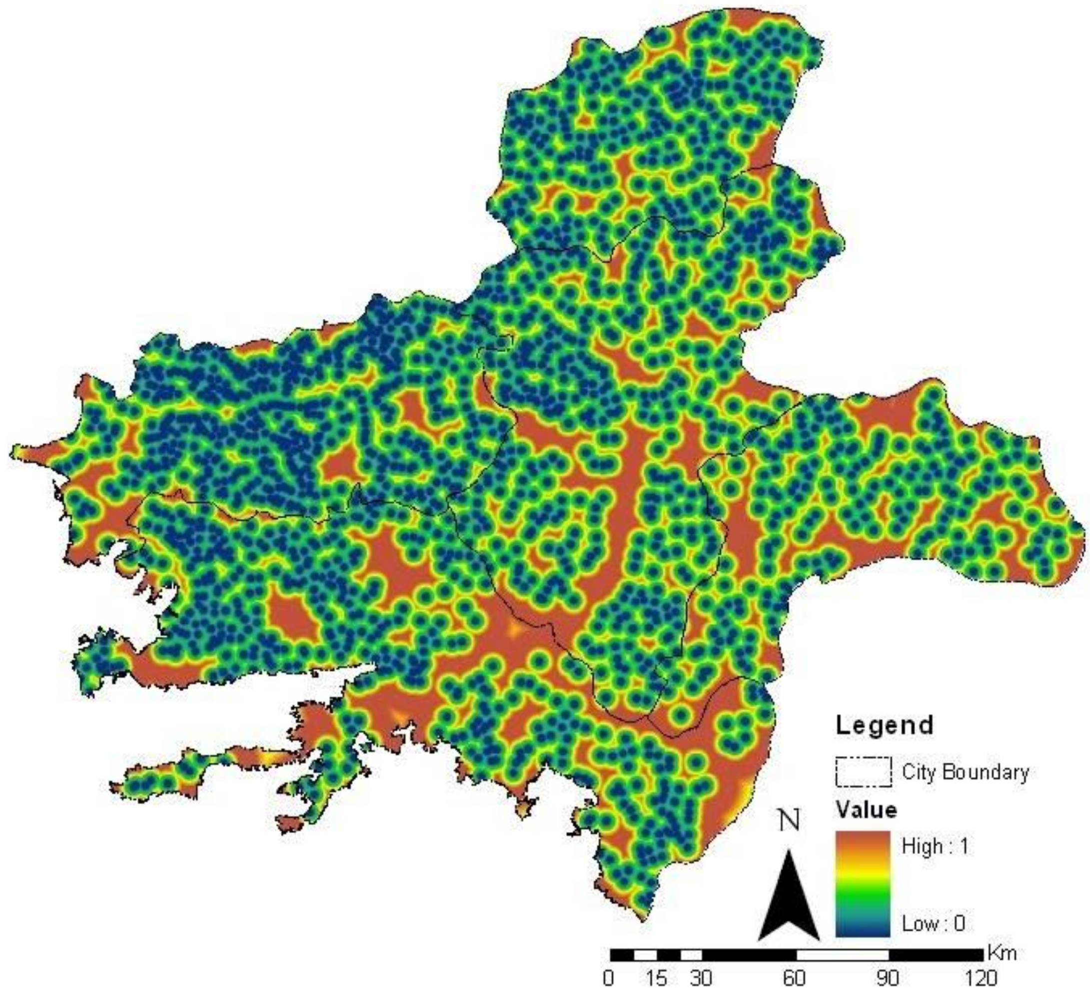


**Figure 4.23** Suitable locations for “Acceptable in terms of proximity to urban area”

Individual satisfaction degrees associated with environmental objectives and economical feasibility criteria are aggregated into OEPI and OSEPI values, respectively. OEPI and OSEPI associated with satisfaction of most of the objectives are given in Figure 4.24 and Figure 4.25, respectively.

In Figure 4.24 and Figure 4.25 dark blue represents a membership value of zero and red represents a membership value of one in the fuzzy sets of “Satisfaction of most of the environmental objectives” and “Satisfaction of most of the economical feasibility criteria” respectively. In other words, red areas indicate that most of the objectives are satisfied. Blue areas generally represent the natural reserves (wetlands, water bodies, forest areas, and agriculture areas). As can be seen from Figures 4.24 and 4.25 a big proportion of the study area does not satisfy most of the environmental and economical objectives. Especially in terms of economical feasibility criteria very little portion of the study area satisfies most of the criteria (i.e. red marked areas in Figure 4.25).

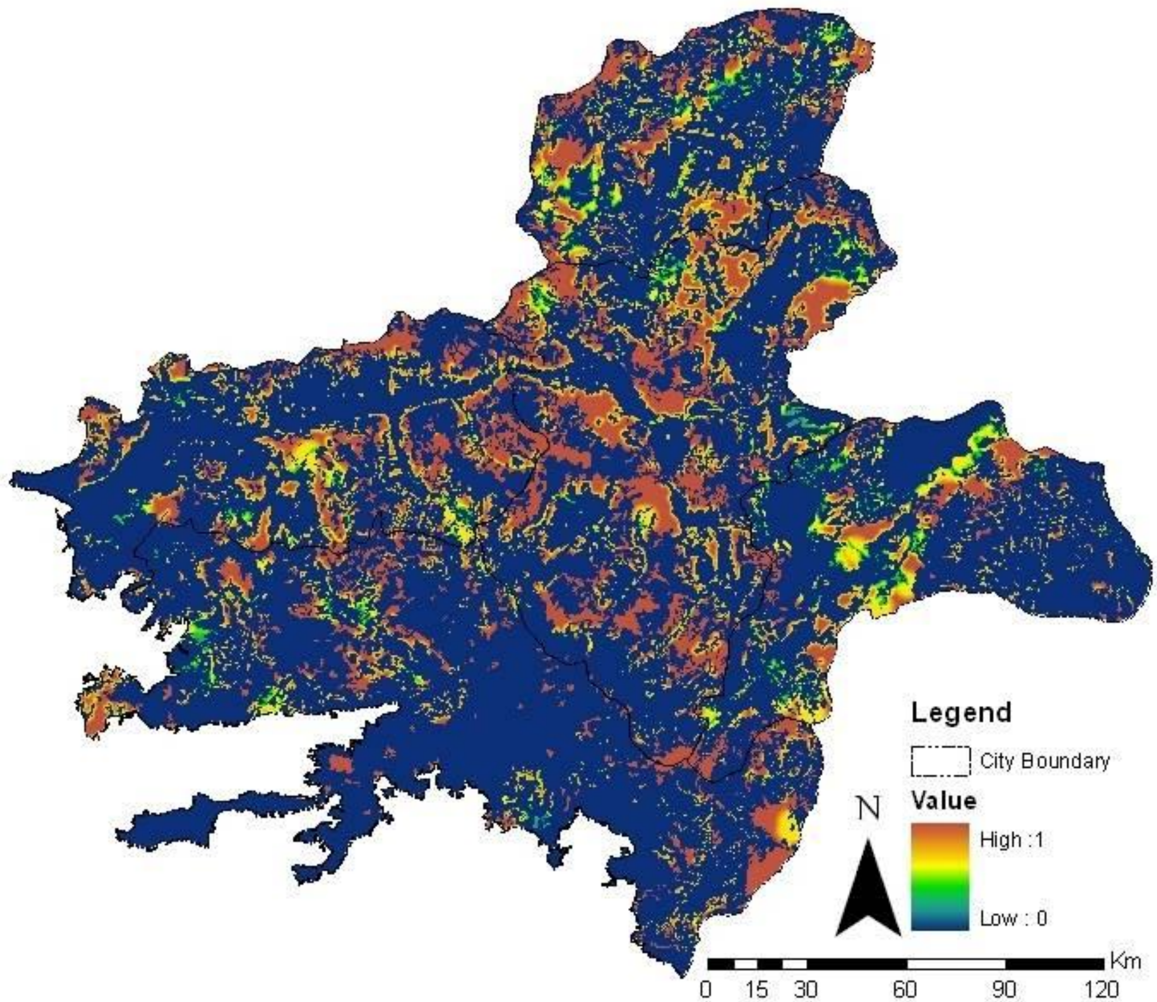


**Figure 4.24** OEPI map for “Satisfaction of most of the environmental objectives”

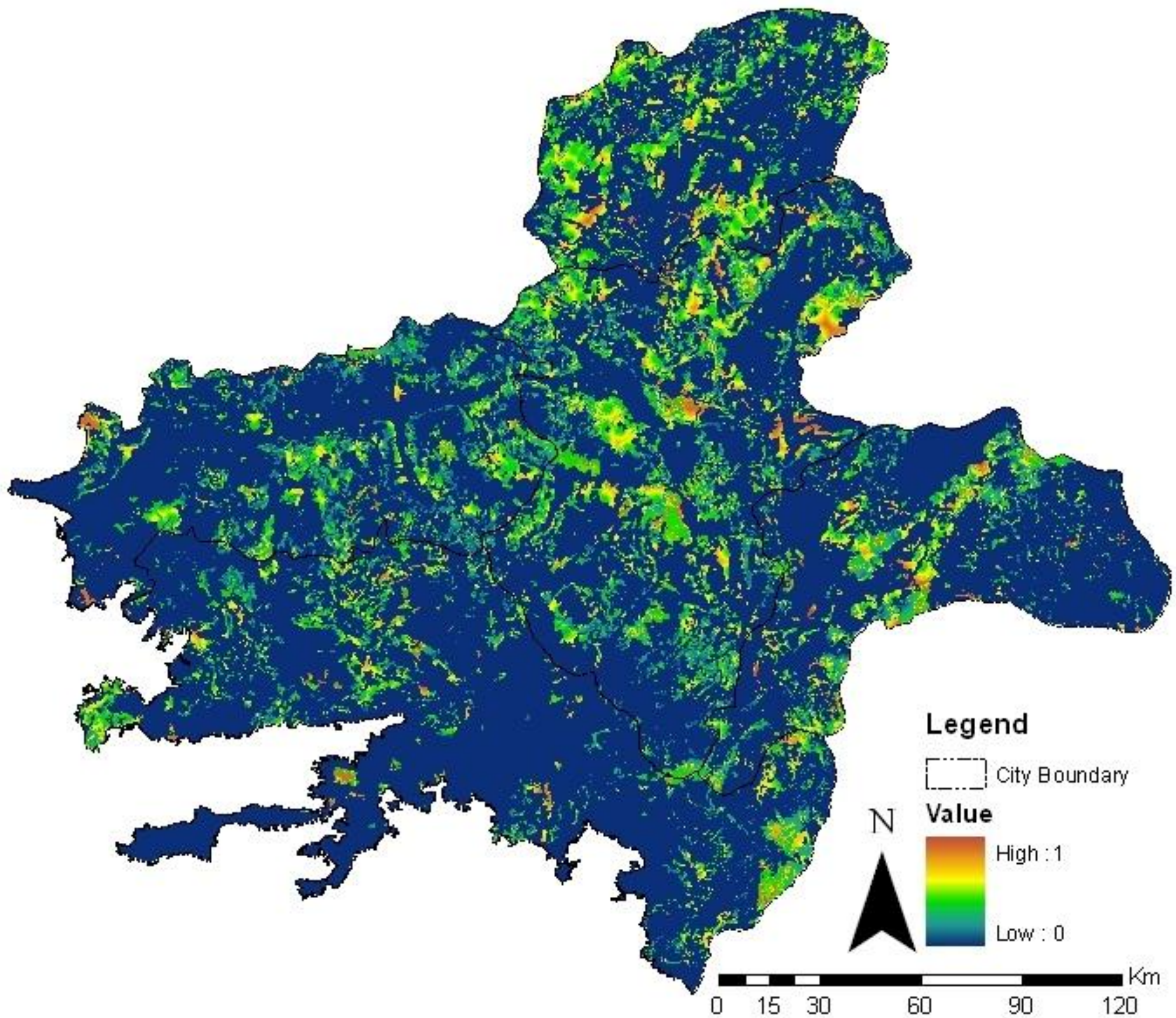


**Figure 4.25** OSEPI map for “Satisfaction of most of the economical feasibility criteria”

After degrees of satisfaction for “Satisfaction of most of the economical feasibility criteria” and “Satisfaction of most of the environmental objectives” are calculated for each grid, these two satisfaction degrees are used to evaluate suitability of each grid point for installation of solar energy power plants using the decision rules given in Table 4.3. As can be seen in Table 4.3, only the grids which satisfy both “Satisfaction of most of the economical feasibility criteria” and “Satisfaction of most of the environmental objectives” with a degree of at least 0.5 are identified as appropriate locations for solar power plants. Therefore, in order to calculate OPI for each grid the “and” aggregation operator is used. Grid values of 0.5 and higher than 0.5 are considered as priority sites for solar energy generation.

The OPI values for each grid are calculated and are provided on the map of the study area in Figure 4.26. To show the priority sites (i.e. grids with an OPI of 0.5 or higher) grids with OPI values lower than 0.5 are excluded from the study area and the resulting map is provided in Figure 4.27. As can be seen in Figure 4.27, most of the yellow and green areas are eliminated from Figure 4.26. Black areas in Figure 4.27 represent the priority sites; in other words these areas are both economically and environmentally feasible locations for solar power plant installations. Currently, there are not any installed large scaled solar power plants in Turkey. However, during the interviews with the General Directorate of Electrical Power Resources Survey and Development Administration, it is learned that new legislation associated with power generation from solar energy will be available in the future (Caliskan, 2009). It is believed that the priority sites map will be useful for the site selection process of solar power plants.

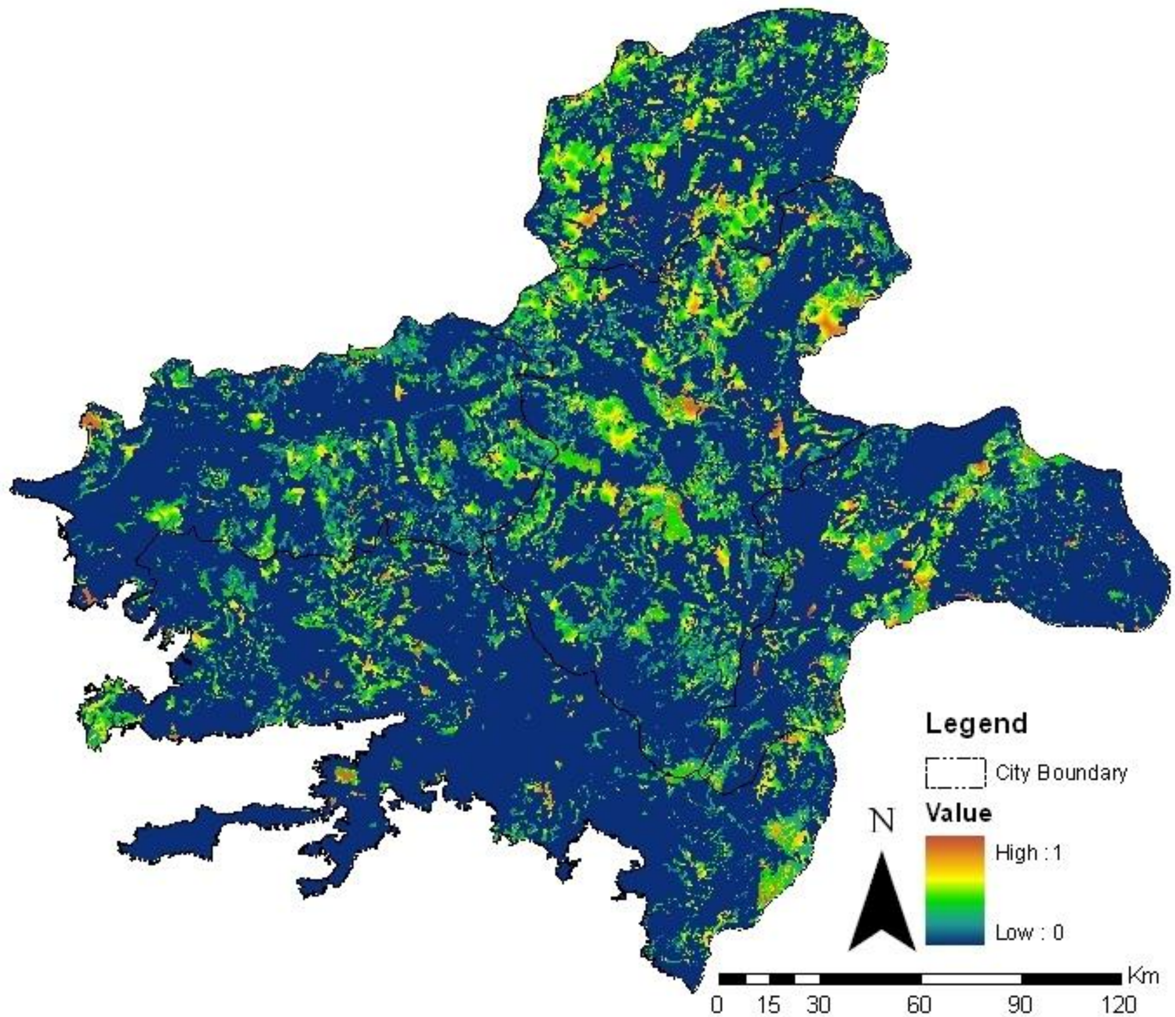


**Figure 4.26** OPI map of the study area

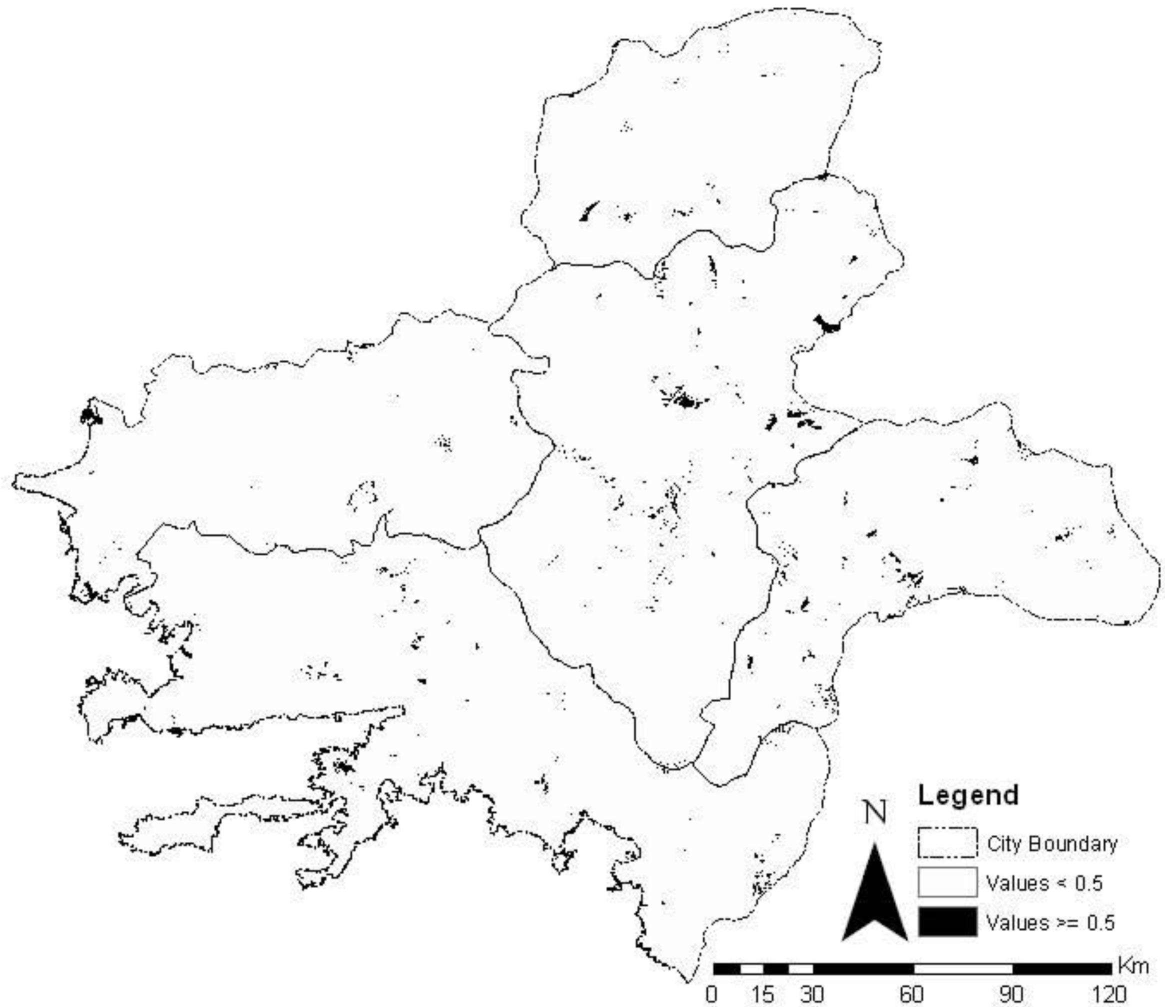


**Figure 4.27** Priority sites within the study area

### 4.3. Wind Energy

As the second case study a decision support tool for site selection of wind turbines is developed by using GIS tools. This study contains site selection of only onshore wind turbines due to the data unavailability for offshore installations. Wind energy potential and environmental fitness/acceptability are used as decision criteria for the site selection process. Potential environmental impacts of wind generation are identified in accordance with Turkish legislations and previous studies and represented as fuzzy objectives of the decision problem. The same study area composed of Uşak, Aydın, Denizli, Muğla, and Burdur provinces is used to demonstrate the proposed site selection procedure for wind turbines.

#### 4.3.1. Methodology

The relevant parts of the general flowchart (Figure 3.1) for wind turbine site selection process are given in Figure 4.28. As can be seen from Figure 4.28 the main difference between the procedures for site selection of solar power plants and wind turbines is that for wind turbines only wind energy potential is used as the economical feasibility criteria. The rest of the procedure is the same with that of solar power plants.

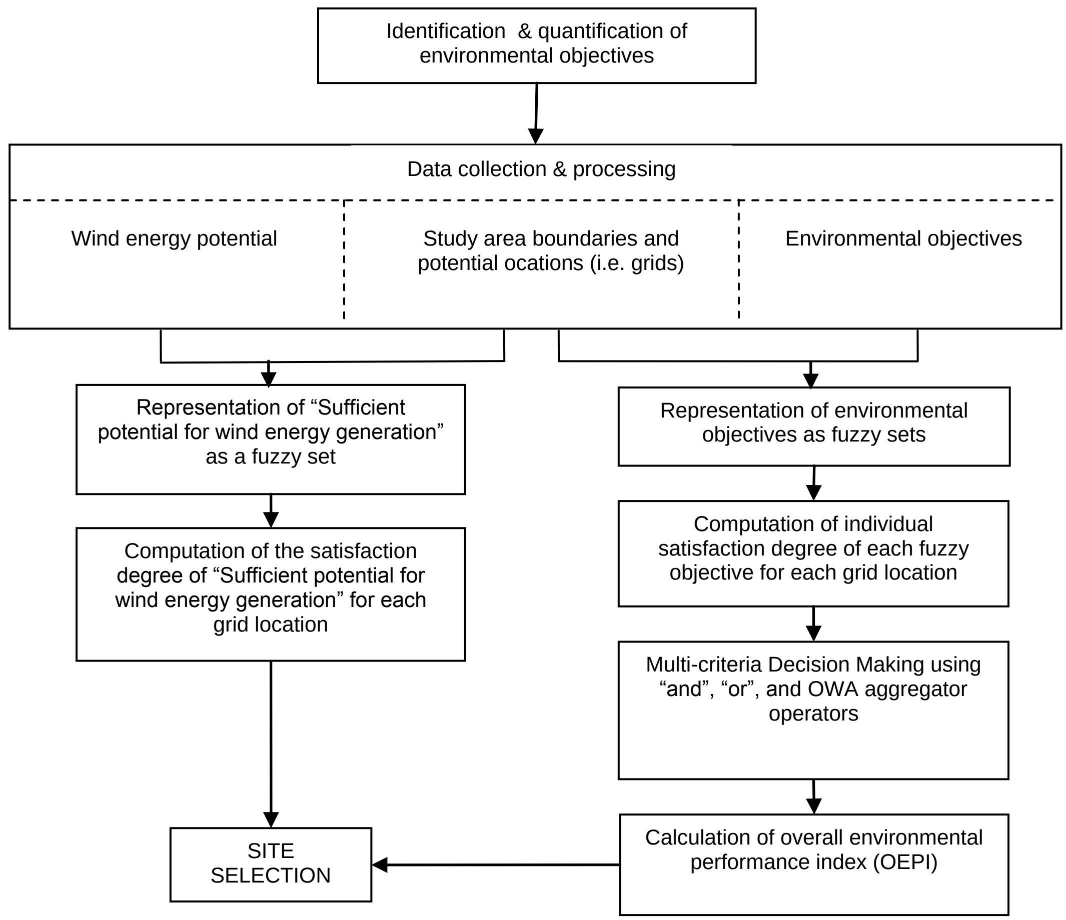


**Figure 4.28** Flowchart of site selection procedure for wind turbines

#### 4.3.1.1. Identification of Environmental Objectives

Environmental objectives associated with energy generation with wind turbines are identified through a literature review about wind turbine installation and government laws and regulations. These objectives are quantified with certain criteria. A criterion is a measurable aspect of a judgment, which makes it possible to characterize and quantify alternatives in a decision making process (Voogd, 1983; Eastman et al., 1993).

Utilization of renewable energy resources such as wind reduces the dependency on other countries for energy generation. Wind energy compared to fossil fuels causes less environmental damage. One of the major contributions of wind energy to environmental protection is through decreasing $CO_2$ emissions (Caralis et al., 2008). Wind turbines do not release any atmospheric emissions while generating power; nonetheless, there are also some negative impacts on both society and ecology (IEA, 2003). The environmental impacts of wind energy which are commonly accepted by scientists are generally listed as effects on animal habitats such as bird collisions, noise generation, visual impact, safety issues, and electromagnetic interference.

Average bird collision to each wind turbine is in the range of 0.1 to 0.6 per year (Web 5). The rotating blades of wind turbines cause blur image on bird's eyes, therefore, birds construe that image as safe to go through, which leads to bird collisions (Morrison and Sinclair, 2004). In order to eliminate bird collisions, wind turbines should be located at a certain distance from bird flyways. According to Yue and Wang (2006), wind turbines must be located at least 500 meters away from wildlife conservation areas. Another suggestion (Clarke, 1991) is that locating wind turbines at a minimum distance of 300 m away from bird habitat can provide bird protection.

A further impact of wind energy on habitat is noise. Although there are some regulations in terms of acceptable noise levels which depend on perception of communities, it is not easy to establish common noise principles (Wrixon et al., 1993). Different authorities have different noise criteria, one of which claims that wind turbines should be located at least 500 m away from nearest habitat (Tester at al., 2005).

Visual impact, another side effect of the wind turbines, varies between individuals. According to Ramirez-Rosado et al. (2008) since the wind energy is constructing the clean energy image, some people might enjoy seeing them; on the other hand, the other people might consider it has adverse impacts on urban landscape. Baban and Parry (2001) state that wind turbines should be located 2000 m away from large settlements because of aesthetic concerns.

Even though a number of serious accidents have occurred, the safety record of wind energy is generally good that most of the accidents are due to poor management or noncompliance with safety regulations (Wrixon et al., 1993). Voivontas et al. (1998) suggest that minimum distance from towns must be 1000 m for safety reasons and the same criteria is valid for reducing the visual impact as well. Nguyen (2007) studied wind energy in Vietnam and concluded that a 2000 m buffer zone around city centers is unsuitable for wind development because of safety and visibility considerations.

According to Nguyen (2007), one other restriction that needs to be taken into account while selecting the location of wind turbines is their proximity to airport areas due to safety and visibility reasons. Nguyen (2007) suggests that wind turbines should be at least 2500 m away from the nearest airport area. In addition, General Directorate of Civil Navigation in Turkey sets some restrictions about structures around airports. Basically, these restrictions aim to protect flight security, human lives, and property. In the first 3000 m zone there should not be any structure such as hospitals, schools or common buildings that may cause reflection. Buildings that are less than 45 m height are allowed with in the second 3000 m zone (General Directorate of Civil Navigation, 2007).

Moreover, wind turbines cause electromagnetic interference by scattering the electromagnetic waves from navigation and telecommunication systems (IEA, 2003). Although television and radio signals may be affected by wind turbines which are located in a 2-3 km zone around the largest installation, today, cable networks or line-of-sight microwave satellite transmissions are eliminating the electromagnetic interference effect of wind energy (IEA, 1987).

#### 4.3.1.2. Quantification of objectives

Although the environmental impacts of wind energy are considerably tolerable with respect to those of conventional energy systems (Tsoutsos et al., 2005), they can be minimized by appropriate site selections for installations of wind turbines  Therefore, before installing wind energy systems, comprehensive analyses should be conducted in order to identify the most favorable locations. Environmental objectives and associated criteria together with the references are given in Table 4.4.

**Table 4.4** Environmental Objectives and Associated Criteria from previous studies

| Environmental objectives | Criteria | Referance |
|---|---|---|
| Acceptable in terms of natural reserves | 1000 m away from areas of ecological value | (Baban and Parry, 2001) |
| | 400 m away from water bodies | (Baban and Parry, 2001) |
| | 250 m away from ecologically sensitive areas | (Yue and Wang, 2006) |
| Acceptable in terms of safety and aesthetics for large city centers | 2000 m away from large settlements | (Baban and Parry, 2001) |
| | 2000 m away from cities, urban centers | (Nguyen, 2007) |
| Acceptable in terms of safety and aesthetics for town centers | Minimum 1000 m away from towns | (Voivontas et al., 1998) |
| Acceptable in terms of safety and aesthetics for airports | 2500 m away from airports | (Nguyen, 2007) |
| | 2500 m away from airports | (Voivontas et al., 1998) |
| Acceptable in terms of noise | 500 m away from nearest habitat | (Tester et al., 2005; Ramirez-Rosado et al., 2008; Yue, 2006) |
| | 400 m away from nearest habitat | (IEA, 1987) |
| Acceptable in terms of bird habitat | at least 500 m away from wildlife conservation areas | (Yue and Wang, 2006) |
| | 300 m from nature reserves to reduce risk to birds | (Clarke, 1991) |

In addition, government laws and regulations play an important role in defining the environmental objectives. In this study, Turkish legislations associated with noise, safety, and natural reserves are used in indentifying environmental objectives associated with wind energy generation. These objectives and associated criteria are given in Table 4.5. Turkish law of electricity generation from renewable energy resources allows construction of wind energy turbines on forest areas, therefore, forest areas are considered environmentally acceptable in this study (Law number: 5346). According to national parks legislation, the structures which have adverse impacts on habitat cannot be built on national parks since these areas have to be preserved. Only the structures for visitors, management and research are allowed (Official Journal Number: 19309).

**Table 4.5** Environmental Objectives and Associated Criteria from regulations

| Environmental Objectives | Criteria | Regulation |
|---|---|---|
| Acceptable in terms of noise | Restriction for industrial areas: between 65dBa to 55dBa | Official journal number: 26809 |
| Acceptable in terms of bird habitat | At least 2.5 km buffer zone to protect ecologic and topographic features | Official Journal Number: 21937 |
| Safe in terms of natural reserves | Structures which have adverse impacts on habitat cannot be built | Official Journal Number: 19309 |
| Acceptable in terms of safety | Minimum distance is 3000 m and maximum distance is 6000 m | General Directorate of Civil Navigation, 2007 |

### 4.3.1.3. Data Collection and Processing

For site selection of wind turbines, different map layers need to be collected. These layers include study area boundaries, wind energy potential, settlement areas, roads, water bodies, natural reserves, etc. The study area is divided into regular grids with certain size and each of these grids is considered as a potential location for installation of wind turbines. In addition, criteria associated with each environmental objective (Table 4.4 and 4.5) need to be represented by criterion maps. For example, a map layer of proximity to airports for “Acceptable in terms of safety and aesthetics for airports” objective is prepared by calculating each grid’s distance to the nearest airport in the study area. Similarly various map layers are prepared for each environmental objective using the associated criteria given in Tables 4.4 and 4.5.

### 4.3.1.4. Representation of Environmental Objectives as Fuzzy Sets

Fuzzy membership functions for seven environmental objectives, as identified in Table 4.4, are generated using the associated criteria given in Tables 4.4 and 4.5 As can be seen from Table 4.4, minimum distances of 250 m, 400 m, and 1000 m are suggested for ecologically sensitive areas, water bodies, and areas of ecologic value, respectively

(Baban and Parry, 2001; Yue and Wang, 2006). All of these criteria are integrated into a single restriction and represented with a fuzzy set named “Acceptable in terms of natural reserves”. The membership function for this fuzzy environmental objective is generated by using this criterion and is given in Figure 4.29.

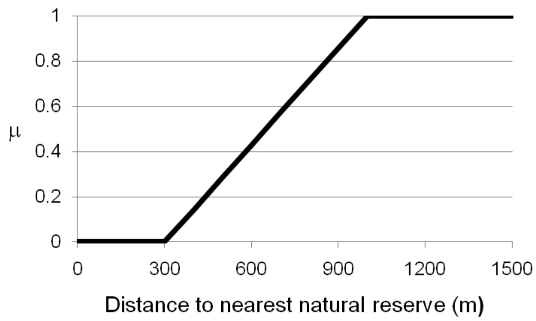


**Figure 4.29** Fuzzy set for “Acceptable in terms of natural reserves”

Another environmental objective is to maintain a power generation scheme which is “Acceptable in terms of safety and aesthetics”. As can be seen from Tables 4.4 and 4.5, different criteria are set for large settlements/urban centers, towns, and airports. In addition to these criteria, minimum and maximum buffer zones around airports are set by the notice of General Directorate of Civil Navigation. Minimum and maximum distances to the airports are set as 3000 m and 6000 m, respectively (General Directorate of Civil Navigation, 2007). Structures which may shine are not allowed in first 3000 m zone, while buildings which are less than 45 m height are allowed in the second 3000 m zone (General Directorate of Civil Navigation, 2007). Three different fuzzy sets, “Acceptable in terms of safety and aesthetics for large city centers”, “Acceptable in terms of safety and aesthetics for town centers”, and “Acceptable in terms of safety and aesthetics for airports” are formed using the criteria provided in Tables 4.4 and 4.5 and are given in Figures 4.30, 4.31, and 4.32, respectively.

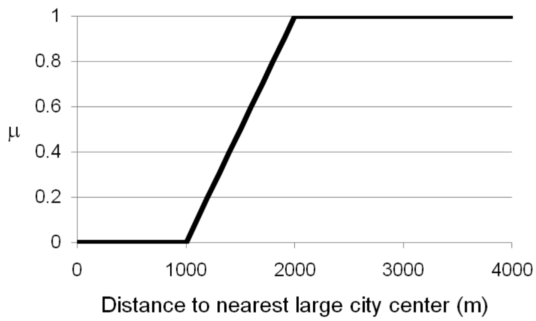


**Figure 4.30** Fuzzy set for “Acceptable in terms of safety and aesthetics for large city centers”


**Figure 4.31** Fuzzy set for “Acceptable in terms of safety and aesthetics for town centers”

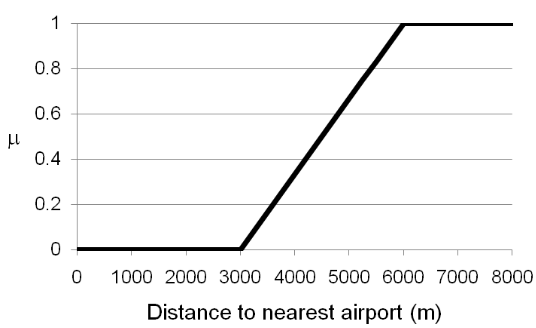


**Figure 4.32** Fuzzy set for “Acceptable in terms of safety and aesthetics for airports”

Noise is another environmental consideration that needs to be evaluated. As can be seen from Table 4.5, even though there are dBa restrictions for industrial areas (between 65 dBa to 55 dBa) in current noise legislation of Turkey, minimum required distances to settlements are not set (Official journal number: 26809). The noise level of a wind turbine which has 1 MW power is expected to be 45 dBa at the distance of 300 m (Environment Foundation of Turkey, 2006). In addition, as can be seen from Table 4.4, 400 m and 500 m are identified as tolerable levels in four different studies. All of these criteria are used to define the membership function of the fuzzy set “Acceptable in terms of noise” and it is given in Figure 4.33.

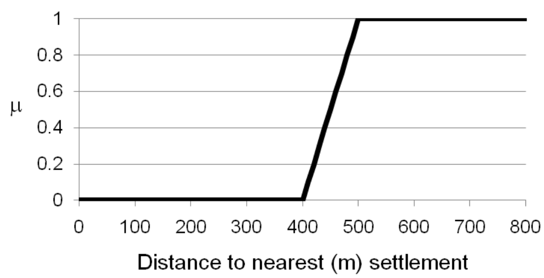


**Figure 4.33** Fuzzy set for “Acceptable in terms of noise”

Bird migration pathways and a certain buffer zone along these pathways are not appropriate locations for wind turbines. In addition to bird migration pathways, wetlands and protection zones are main locations of bird habitat. Wetlands and protection zones are determined by Ministry of Environment and Forestry. According to the Turkish legislation about wetlands (Official Journal Number: 21937) there must be at least 2.5 km buffer zone to protect ecologic and topographic features of these areas (Table 4.5). The fuzzy membership function for “Acceptable in terms of bird habitat” is formed by using the information provided in Tables 4.4 and 4.5, and is given in Figure 4.34.

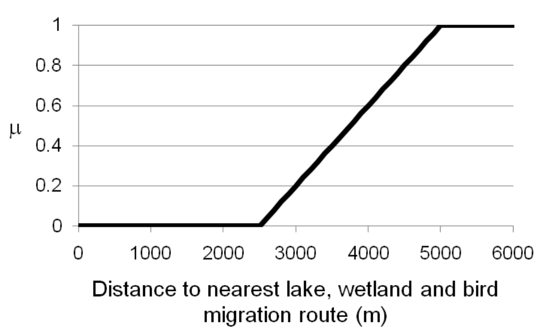


**Figure 4.34** Fuzzy set for “Acceptable in terms of bird habitat”

#### 4.3.1.5. Computation of individual satisfaction degrees

The generated membership functions are used to compute individual satisfaction degree of each potential location (i.e. grid point) for each environmental objective in GIS. To calculate and store all the required information for individual satisfaction degrees of each fuzzy environmental objective, a separate layer is created in GIS. For example, in the layer corresponding to "Acceptable in terms of noise", data related with housing areas is stored since the noise level of the wind turbines should not disturb the population in the residential area. The individual satisfaction degree of each fuzzy environmental objective for each grid is evaluated by using the data stored in these layers.

Membership function of the fuzzy environmental objective is used to determine the fulfillment degree of this objective by each potential location. These individual satisfaction degrees are recorded in a separate column in the GIS database. The next step is to aggregate these individual satisfaction degrees into an OEPI.

#### 4.3.1.6. Representation of wind energy potential as a fuzzy set

Wind energy potentials at potential locations (i.e. grid points) are not included in the OEPI calculations. However, while performing site selection, both the wind energy potential and environmental acceptability/fitness need to be considered. A location which does not have sufficient wind energy potential is not an appropriate location for wind turbines no matter how high its OEPI is. Thus, the next step is to obtain the available wind energy potential map of the study area.

During interviews with the General Directorate of Electrical Power Resources Survey and Development Administration, it became clear that economically feasible power values for generating wind energy in Turkey are between 300 $\dot{P}/A$ and 400 $\dot{P}/A$. However, in Europe satisfactory values start from 200 $\dot{P}/A$ (Çobancıoğlu, 2009; Malkoç, 2009). In order to quantitatively represent sufficient/feasible wind energy potential, a fuzzy set named "Sufficient potential for wind energy generation" is formed using this information. The membership function of this fuzzy set is given in Figure 4.35. The wind energy potential map of the study area is used to generate wind potential layer in GIS. "Sufficient potential for wind energy generation" fuzzy set and the wind energy potential layer is used together to calculate a degree of satisfaction for “Sufficient potential for wind energy generation”.

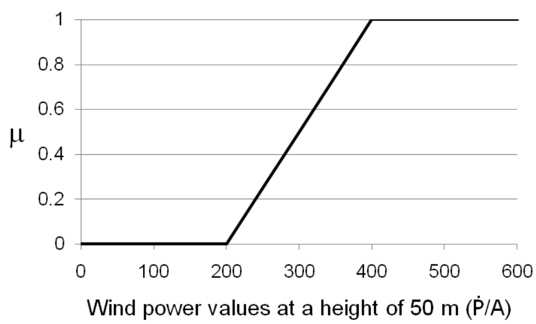


**Figure 4.35** Fuzzy set for “Sufficient potential for wind energy generation”

#### 4.3.1.7. Multi-criteria Decision Making (MCDM)

In this case study, “and”, “or”, and OWA (for “satisfaction of most of the objectives”) operators are used as MODM tools in evaluating alternatives with respect to various fuzzy environmental objectives. Utilization of the quantifier “most” is explained in detail and provided in Section 3.4 of this thesis. Therefore, it is not provided here again.

#### 4.3.1.8. Site Selection

At the end of the procedure given in Figure 4.28, each grid is associated with a degree of satisfaction for “Sufficient potential for wind energy generation” and “Satisfaction of most of the environmental objectives” (i.e. OEPI). Each grid point need to be evaluated based on these two criteria. Aggregation of satisfaction degrees of these two criteria is another decision making process. The same decision criteria used for solar power plants is used for wind turbines as well; however for the sake of completeness it is provided here again in Table 4.6.

**Table 4.6** Site selection criteria for wind energy systems

| Degree of satisfaction for "Sufficient potential for wind energy generation" | Degree of satisfaction for "Satisfaction of most of the environmental objectives" | DECISION for the grid (i.e. alternative) |
|---|---|---|
| 0.0-0.5 | 0.0-0.5 | Eliminate – due to both insufficient potential and environmental concerns. |
| 0.0-0.5 | 0.5-1.0 | Eliminate – due to insufficient potential. |
| 0.5-1.0 | 0.0-0.5 | Eliminate for now – due to environmental concerns. Consider remedial actions and reevaluate. |
| 0.5-1.0 | 0.5-1.0 | Mark as priority site for wind energy generation. |

As can be seen from Table 4.6, only the grid points which satisfy both "Sufficient potential for wind energy generation" and "Satisfaction of most of the environmental objectives" with a degree of at least 0.5 are identified as appropriate wind turbine locations. These grids can be referred to as "priority sites" for wind energy generation. Priority sites can be identified in GIS environment using the "and" operator with the following procedure: Degrees of satisfactions for "Sufficient potential for wind energy generation" and "Satisfaction of most of the environmental objectives" are aggregated by the "and" operator to give an OPI and grids with an OPI of 0.5 and higher are selected.

### 4.3.2. Example Application for Wind Turbines

To demonstrate the proposed site selection methodology for wind turbines, the same study area used for site selection of solar power plants is used. A detailed map of the study area and location of the study area within Turkey are given in see Figure 4.3 and Figure 4.4. High wind power potential of the study area makes it attractive for renewable energy investors. The current wind potential map of the study area is obtained from General Directorate of Electrical Power Resources Survey and

Development Administration and is given in Figure 4.36. Wind energy potential map contains available power values at a height of 50 m.

First, associated layers for wind energy potential, settlement areas, roads, water bodies, natural reserves, wetlands, bird migration pathways, and airports are obtained for the study area. As explained earlier, environmental criteria associated with wind energy generation are identified and represented as fuzzy sets (see Figures 4.29 to 4.35). Then 250 m point grids were created for the whole study area in ArcGIS 9.2 software. Individual satisfaction degrees of each fuzzy environmental objective for each grid location are evaluated by using GIS tools and they are aggregated into an OEPI. The attitude of the decision maker are included in the decision making process through utilization of different aggregation operators. In this study, “Satisfaction of most of the environmental objectives” (i.e. OWA), “Satisfaction of all the environmental objectives” (i.e. “anding”) and “Satisfaction of any of the environmental objectives” (i.e. “oring”) are investigated. OEPI of wind energy associated with “Satisfaction of most of the environmental objectives” is given in Figure 4.37.

In Figure 4.37, red represents a membership value of 1 while blue represents a membership value of 0 in the fuzzy set “Satisfaction of most of the environmental objectives”. In other words, the red grids are the ones where satisfaction of most of the environmental objectives is fully accomplished. As can be seen from Figure 4.37, a big portion of the study area (i.e. red regions) satisfies most of the environmental objectives. The vertical yellow band passing through the study area represents a bird migration route. As expected the compatibility of this band with “Satisfaction of most of the environmental objectives” fuzzy set is less than one (i.e. it is marked with yellow instead of black on the map). Similarly, areas close to lakes and other water bodies, large city centers, natural reserves, town centers, airports are marked with different tones of yellow and green which indicate various satisfaction degrees in between zero and one. The tones between red to blue is governed by the proximity of the grid point to these locations.

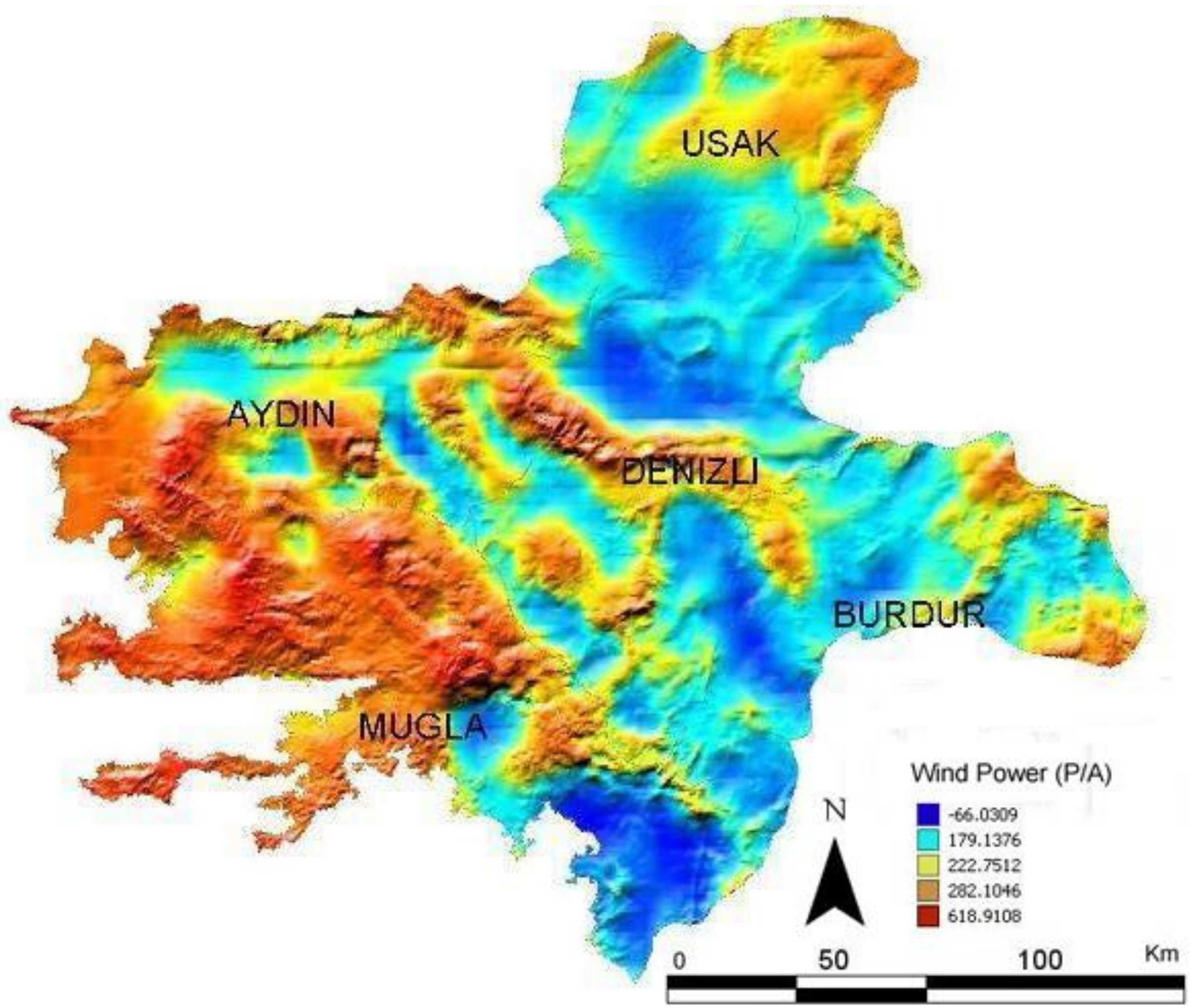


**Figure 4.36** Current wind potential for the study area

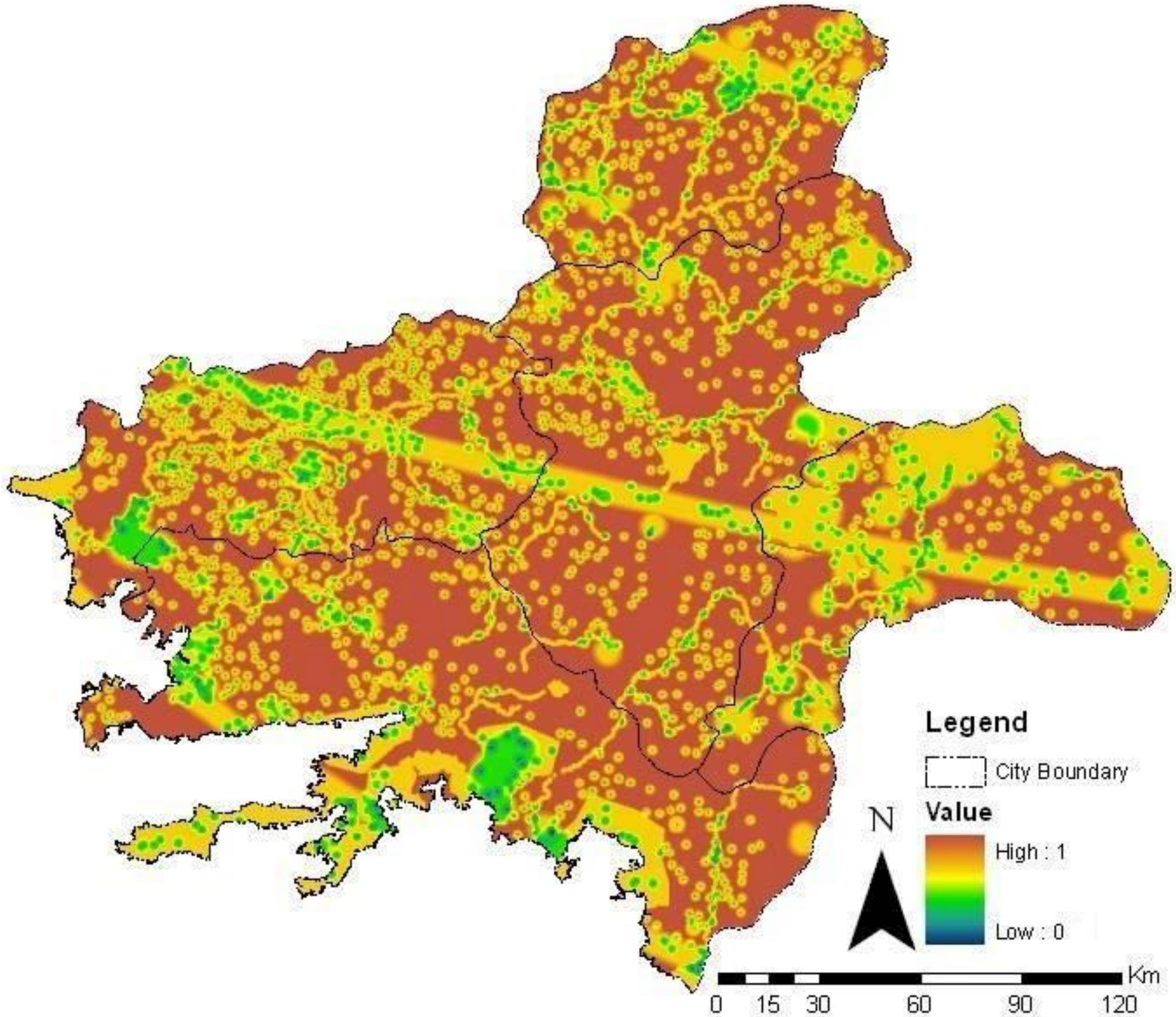


**Figure 4.37** OEPI map for “Satisfaction of most of the environmental objectives”

Aggregation operators “and” and “or” are used as well to generate OEPI for “Satisfaction of all of the environmental objectives” and “Satisfaction of any of the environmental objectives”, respectively. The OEPI maps for “and” and “or” operators are given in Figures 4.38 and 4.39, respectively. The “and” operator represents the worst case scenario. As can be seen from Figure 4.38, the bird migration route is marked with a blue band (i.e. membership function value for “Satisfaction of all of the environmental objectives” fuzzy set is zero). Since “Satisfaction of all of the environmental objectives” is required and the bird migration route has an individual satisfaction degree of zero for “Acceptable in terms of bird habitat” fuzzy objective, the overall satisfaction degrees for the grids located in this bird migration route band become zero. Similarly, all water bodies, large city centers, natural reserves, town centers, airports are marked with blue zones in Figure 4.38. Not having many yellow and green zones in Figure 4.38, indicates that most of the grid points either satisfy all the fuzzy objectives (i.e. overall satisfaction degree is one and consequently the grid is marked with red) or there is at least one fuzzy objective which is not satisfied at all (i.e. the grid has an individual satisfaction degree of zero for at least one of the fuzzy objectives). “Satisfaction of any of the environmental objectives” requirement produces a map which is completely red (see Figure 4.39). This indicates that all the alternatives (i.e. potential locations) fully satisfy at least one of the fuzzy objectives. Thus, OEPI for all grids are one.

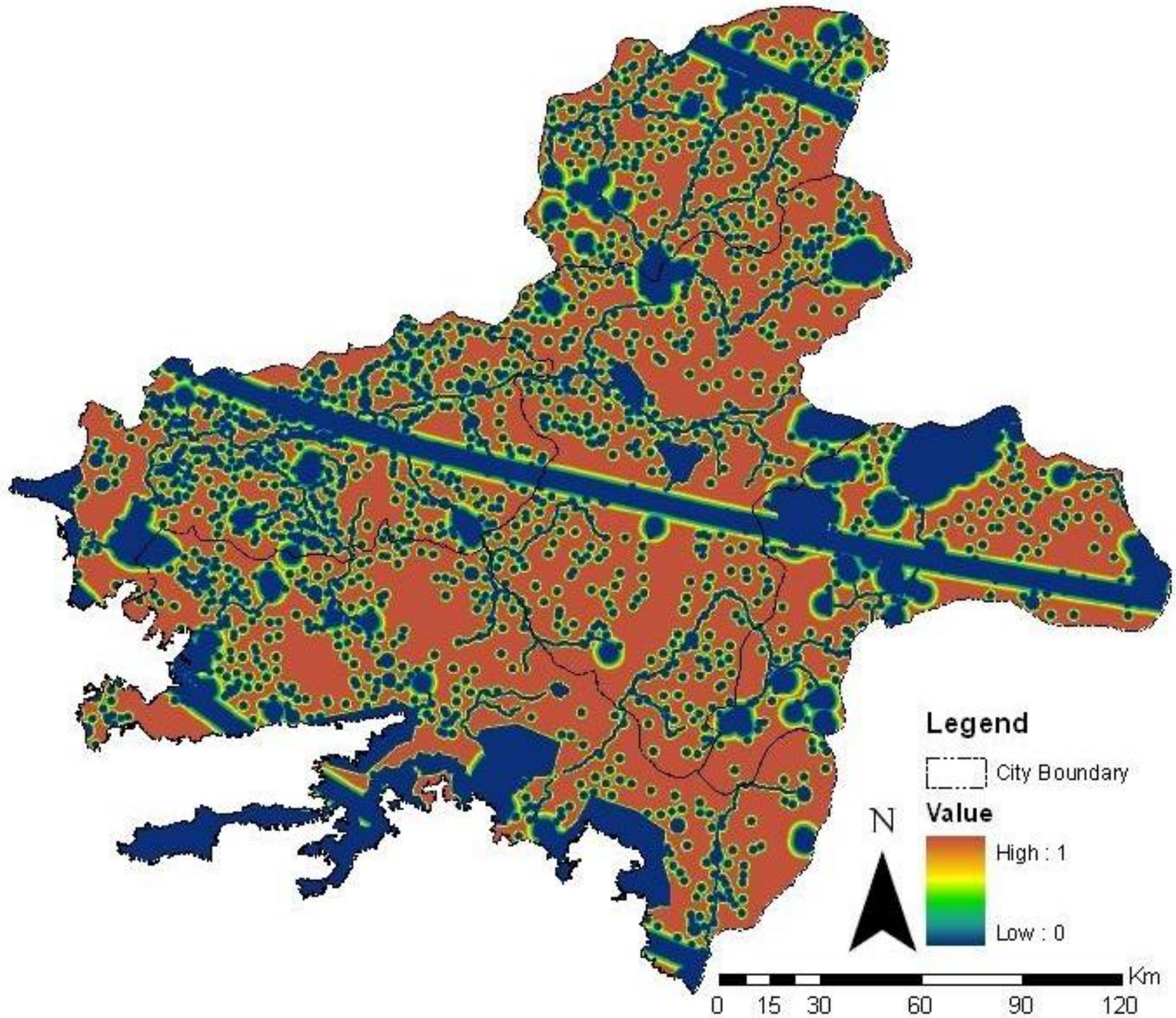


**Figure 4.38** OEPI map for “Satisfaction of all of the environmental objectives”

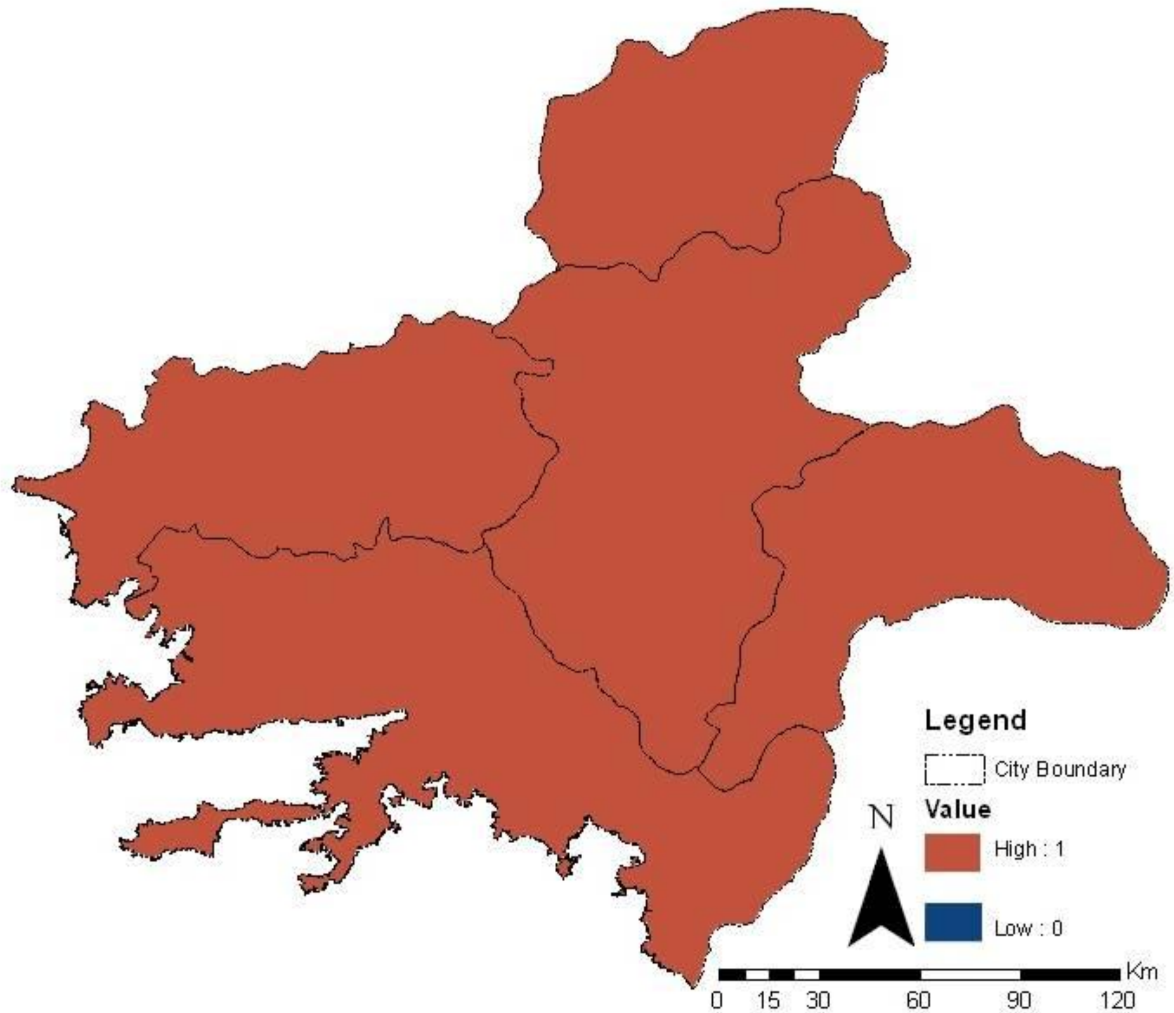


**Figure 4.39** OEPI map for “Satisfaction of any of the environmental objectives”

Wind energy potential map of the study area (Figure 4.36) is used together with the membership function of "Sufficient potential for wind energy generation" fuzzy set and a satisfaction degree is calculated for each grid point. The satisfaction degree is an indication of how much each grid location belongs to "Sufficient potential for wind energy generation" fuzzy set. In other words, the fuzzy set converts wind energy potential of each grid into a value in the range [0, 1]; 0 representing not sufficient potential for wind energy generation and 1 representing completely sufficient potential for wind energy generation.

Degrees of satisfaction for "Sufficient potential for wind energy generation" and "Satisfaction of most of the environmental objectives" (i.e. OEPI) for each grid point together with decision criteria given in Table 4.6 are used to evaluate suitability of each grid point for installation of wind turbines. As can be seen from Table 4.6, only the grids which satisfy both "Sufficient potential for wind energy generation" and "Satisfaction of most of the environmental objectives" with a degree of at least 0.5 are identified as appropriate wind turbine locations. Thus an OPI is calculated for each grid point by aggregating the satisfaction degrees of "Sufficient potential for wind energy generation" and "Satisfaction of most of the environmental objectives" with the "and" operator. Grid points with an OPI value of 0.5 can be referred to as priority sites for wind energy generation.

OPI for each grid point of the study area are provided in Figure 4.40. As can be seen from Figure 4.40, the OPI values range between 0 and 1. Grid points with 0 OPI are locations where environmental criteria and sufficiency of wind potential completely fails, while grid points with an OPI of 1 are the best locations for installing wind turbines. Acceptable grid points for wind turbines are evaluated using the decision criteria provided in Table 4.6. The grid points with an OPI of 0.5 and higher are selected as priority sites and given in Figure 4.41. As can be seen from Figure 4.40, green areas (i.e. grids with an OPI of 0.5 and smaller) of Figure 4.40 are eliminated from the priority sites. However, it should be noted here that these grids may be turned into priority sites with implementation of appropriate environmental measures. Thus, these locations require further study and reevaluation. Already existing wind turbine locations are marked on Figures 4.40 and 4.41. As can be seen from Figure 4.41, some of the existing wind turbines are located on the priority sites identified in this case study. It can be concluded that locations of these existing turbines are acceptable with respect to both sufficiency of wind potential and satisfaction of environmental objectives.

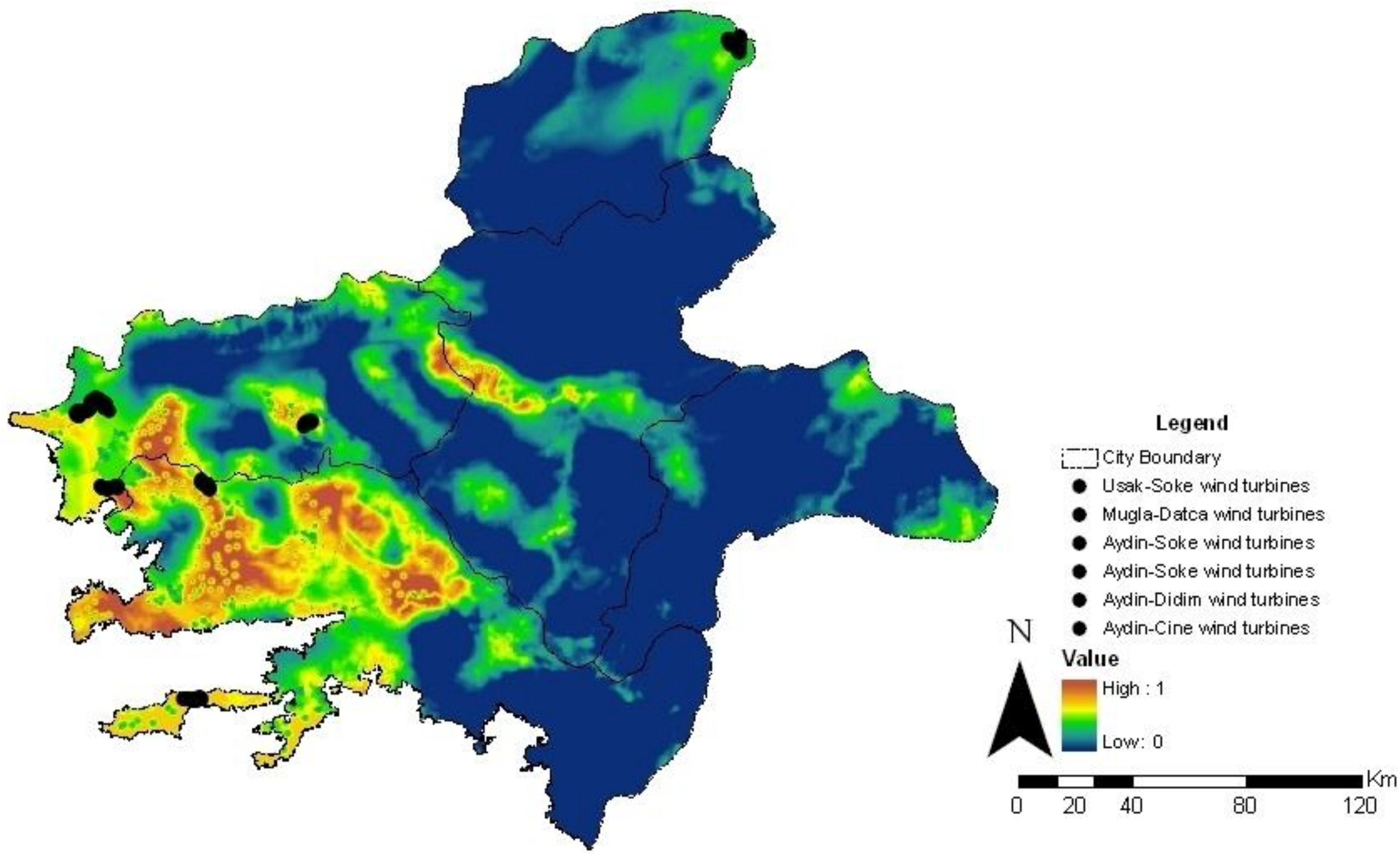


**Figure 4.40** OPI map

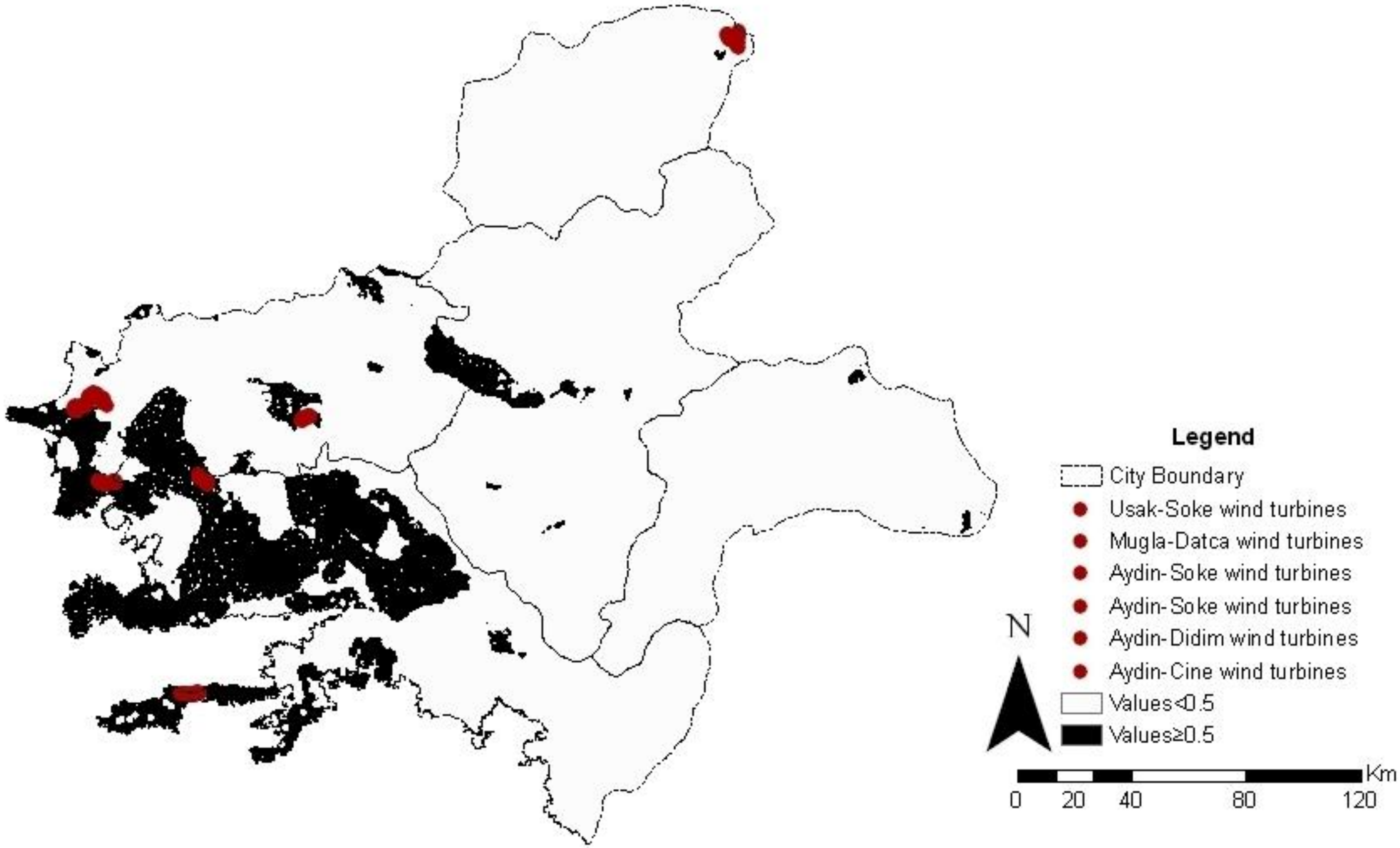


**Figure 4.41** Priority sites

### 4.4. Hybrid Wind-Solar Energy Systems

Feasible locations within the study area for wind turbines and solar power plants are identified separately. However, considering advantages of hybrid systems which are presented in the previous researches, priority sites for wind and solar energy are combined to identify environmentally and economically suitable locations for constructing hybrid systems composed of wind turbines and solar power plants. Priority maps of wind and solar energy are overlaid by using “bitwise and” tool in ArcGIS 9.2 software in order to identify priority sites for hybrid systems of wind and solar energy which are provided in Figure 4.42.

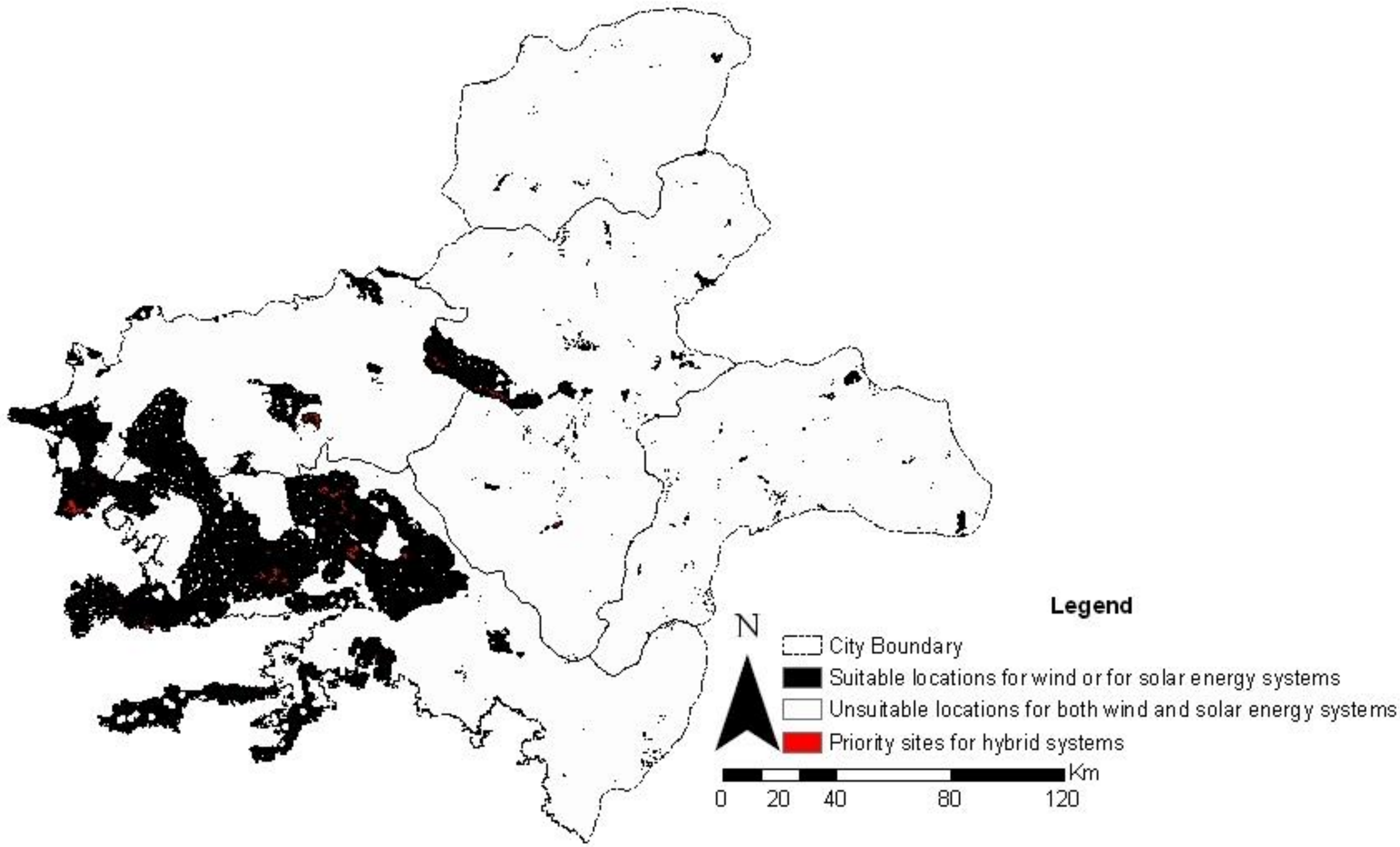


**Figure 4.42** Priority sites for hybrid systems of wind and solar energy

As can be seen in Figure 4.42, feasible locations for wind-solar hybrid systems are marked with red. Black areas indicate suitable locations either for wind turbines or for solar power plants. If a hybrid wind-solar system is constructed on one of these red spots the energy generation efficiency will increase and discontinuities in energy generation may be minimized.

# CHAPTER 5

# RESULTS AND DISCUSSIONS

It is well accepted that RES may assist to overcome the environmental problems associated with conventional energy systems. Today, many countries around the world utilize RES and integrate RES into their current energy policies. However, it became clear that RES may have various negative environmental impacts which are mostly related to the geographical locations of renewable energy facilities. Therefore, in this thesis a decision support tool for site selection of wind and solar energy generation facilities is proposed. Decision support tool that utilizes a fuzzy decision making approach allows combined assessment of economical and environmental criteria in GIS environment.

During the interviews with the General Directorate of Electrical Power Resources Survey and Development Administration, it became clear that renewable energy investments, particularly, those for wind energy are expected to increase in the near future. However, to our knowledge, there is not any decision support system that can provide guidance to the authorities in evaluating the RES applications. We believe that the proposed decision support tool may provide useful guidance both for the investors and the authorities in identifying suitable locations for RES with respect to environmental and economical aspects.

Environmental and economical criteria related with wind and solar energy generation facilities are identified through a detailed review of previous studies, Turkish Laws and Legislations, and interviews with the General Directorate of Electrical Power Resources

Survey and Development Administration. These environmental and economical criteria are represented by fuzzy sets and an individual satisfaction degree for each alternative location with respect to these criteria is calculated by using the membership functions of the identified criteria. Thus, the analysis is highly dependent on the selected membership functions that represent the environmental and economical criteria. It should be noted here that the membership functions are developed using the results of previous studies, current Turkish laws and regulations, and personal judgment in this study. The membership functions need to be revised when new information becomes available.

As the final step, these individual satisfaction degrees are aggregated into overall performance values for environmental and economical criteria using different aggregator operators for wind energy and OWA for solar energy. Finally these two overall performance values are used together to evaluate the priority sites (i.e. environmentally and potentially favorable sites) for wind and solar energy generation facilities. The proposed methodology is tested on a case study area. The case study area is composed of Uşak, Aydın, Denizli, Muğla, and Burdur provinces in Turkey. Priority sites within the study area are identified for wind turbines, solar power plants, and hybrid systems.

In the first case study, site selection for solar power plants within the study area is realized. The study area is divided into 250 m by 250 m grids where each grid represents an alternative location for wind turbine installations. In this example, various economical feasibility criteria (i.e. solar energy potential, slope, proximity to transmission line and urban areas) together with a set of environmental objectives are used to identify priority sites for solar power plants. First, the individual satisfaction degrees of the identified environmental objectives are aggregated into an OEPI for each alternative location using the OWA aggregator (see Figure 4.24). As the second step, individual satisfaction degrees of each alternative location with respect to the economical feasibility criteria are aggregated into an OSEPI value (see Figure 4.25). Finally, OPI is calculated by aggregating the OEPI and OSEPI using the “and” aggregator (see Figure 4.26). Priority sites are specified using the following decision criteria: sites with an OPI of 0.5 or higher are suitable locations for solar energy generation facilities in terms of environmental and economical criteria (see Figure 4.27).

It should be noted here that, each identified priority site is a 250 m by 250 m area. Additional analysis need to be carried out to specify exact location of the power plant within the priority site.

Currently, large scaled solar energy facilities do not exist in Turkey due to the financial burden of solar technologies. However, as solar energy technologies become financially affordable for the investors, it is expected to have large scale solar power plant installations in Turkey. Therefore, results of this thesis may assist decision makers to assign licenses for future solar energy facilities. The proposed methodology is expected to result in more informed decisions both for investors and the governing authorities.

In the second case study, site selection for wind turbines is realized. First, individual satisfaction degrees of each alternative location with respect to the identified environmental objectives are calculated and then aggregated into an OEPI by using “and”, “or” and OWA aggregators. The results show that, all of the study area is feasible in terms of environmental objective when “or” aggregator is used (see Figure 4.39) while study area excluding all the water bodies, large city centers, natural reserves, town centers, airports is feasible when “and” aggregator is used (see Figure 4.38). These two aggregators represent two extreme cases. However, in real world, the decision maker usually is willing to take some risk and accept satisfaction of most of the environmental objectives. This is accomplished by the OWA aggregator. Areas identified as feasible by the OWA aggregator satisfy most of the environmental objectives (see Figure 4.37). OWA aggregator is not as strict as the “and” operator, however it is not as tolerant as the “or” operator. Satisfaction of each of the environmental objective impact the decision and higher satisfaction of each objective result in a higher overall satisfaction, but complete failure of one of the environmental objectives does not result in a zero overall satisfaction, only decreases the degree of overall satisfaction.

As the second step, the impact of wind potential is integrated into the evaluation process and an OPI for wind turbines is calculated by aggregating wind potential which is represented by a fuzzy set called “Sufficient potential for wind energy generation” and the OEPI. To aggregate the OEPI and satisfaction degree of “sufficient potential for wind energy generation” the “and” operator is used (see Figure 4.40). Alternative locations (i.e. grid points) having an OPI of 0.5 or higher are identified as priority sites (see Figure 4.41). Priority sites are the sites which are suitable with respect to both wind potential and environmental concerns.

The final analysis is to assess suitability of the locations of the existing wind turbines in the study area. Operating wind turbines are marked on the priority sites map. The results show that some of the operating wind turbines are not located on the priority sites identified in this thesis. For example, all of the wind turbines in Uşak-Soke, 3 wind turbines in Muğla-Datca, 36 wind turbines in Aydın-Soke, 7 wind turbines in Aydın-Didim are not located on priority sites. This is because Energy Market Regulatory Authority and the General Directorate of Electrical Power Resources Survey and Development Administration are assigning permits considering primarily wind energy potential and economic feasibility (Web 13). Environmental impacts are not considered in assigning permits. The proposed approach may assist the authorities in evaluating alternative applications in terms of both wind potential and environmental concerns.

As a final analysis priority sites within the case study area for hybrid systems (i.e. an energy generating facility which combines wind turbines and solar power plants) are identified. Hybrid systems increase energy generation efficiency by decreasing negative impacts of weather and climatic conditions on a wind turbine or a solar power plant alone. In this thesis, priority sites for hybrid systems are obtained by overlaying priority sites maps of wind and solar energies and can be seen in Figure 4.42 of this thesis. Locating hybrid systems at these priority sites is expected to increase the efficiency of energy generation while minimizing negative impacts of these systems on the environment.

To evaluate environmental and economical constraints, various analyses need to be conducted using spatial data. GIS provides extensive tools to conduct such analyses. Moreover, in real life representation of environmental and economical criteria using crisp sets is not realistic. Representation of such complex phenomena can better be achieved by using fuzzy sets. Thus, in this thesis implementation of fuzzy decision making tools is realized in GIS environment, namely ArcGIS 9.2 which has some build-in tools to conduct various operations such as weighted sum, weighted overlay etc. However, it does not have the necessary tools to carry out operations required for OWA aggregation. Thus Excel is used in combination with ArcGIS 9.2 to effectively conduct OWA aggregation. To ease such calculations and save time a number of new GIS tools are developed. These new tools assist decision makers to implement the proposed methodology easily and in a timely manner.

# CHAPTER 6

# CONCLUSIONS AND RECOMMENDATIONS

Today, Energy Market Regulatory Authority and the General Directorate of Electrical Power Resources Survey and Development Administration assign permits for wind turbines according to economical and potential concerns such as dominant wind direction, stability of the wind speed, type of wind turbines etc. (Cobancioglu, 2009; Malkoc, 2009). However, economic feasibility needs to be considered together with environmental fitness in order to achieve sustainable energy generation. A decision support system to simultaneously evaluate economical feasibility and environmental criteria in identification of suitable locations for RES is developed in this thesis. To our knowledge there is not any decision support system in Turkey which is available for the investors or the authorities; thus the proposed tool is of practical importance.

Application of the proposed approach for the case study for site selection of wind turbines demonstrated that all of the wind turbines in Uşak-Soke, 3 of the wind turbines in Muğla-Datca, 36 of the wind turbines in Aydın-Soke, and 7 of the wind turbines in Aydın-Didim within the study area are not located on the identified priority sites (see Figure 6.1).

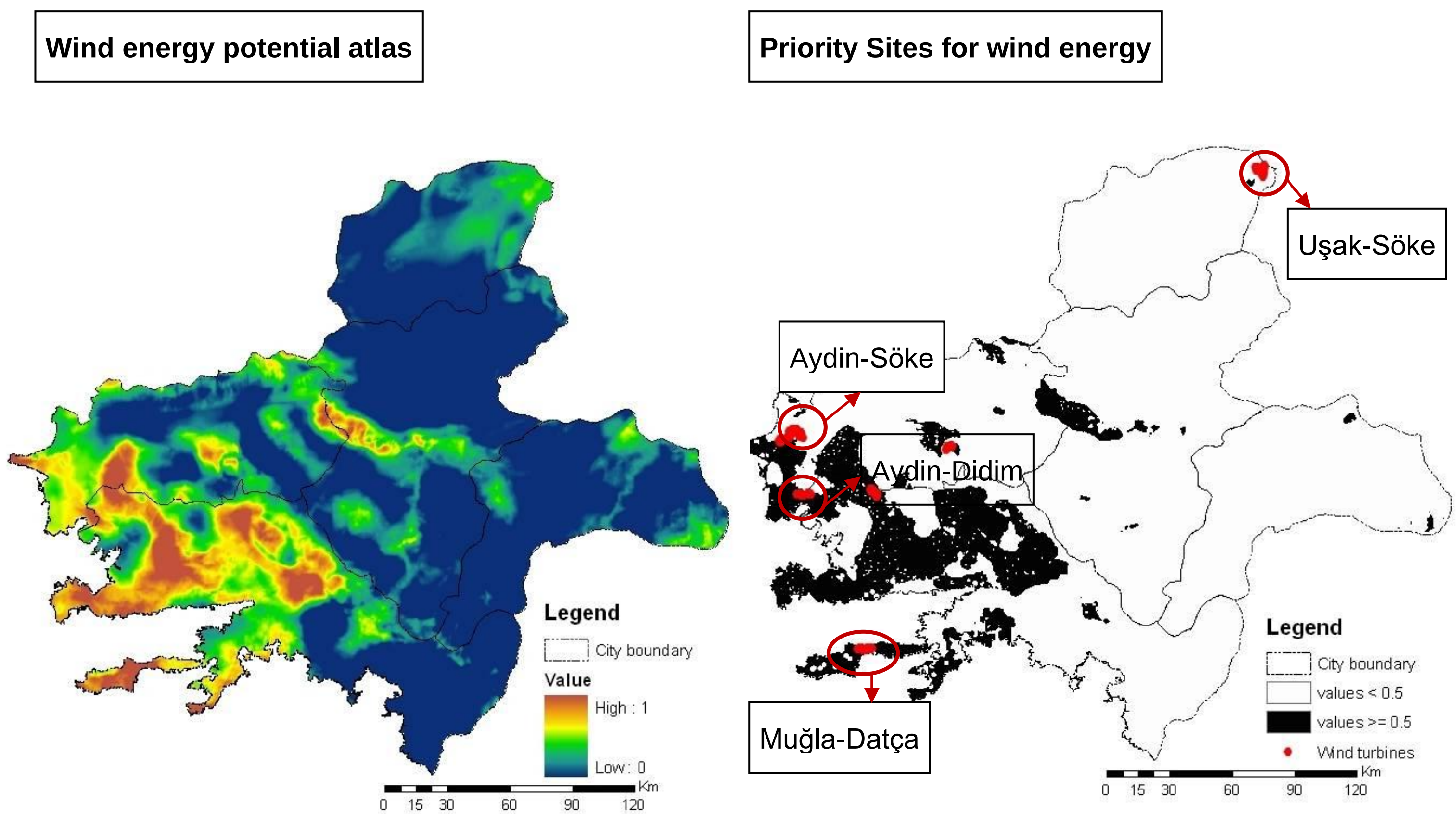


**Figure 6.1** Comparison of current wind turbine locations

Since, the site selection process is solely based on wind potential, operational wind turbines pose risk of generating negative environmental impacts. As can be seen in Figure 6.1, black represents the priority sites which satisfy most of the environmental objectives and sufficient wind potential. Therefore, a big proportion of the southwest region within the study area is identified as feasible locations for future wind turbine constructions. Utilization of the proposed approach in the future may help both investors and the governing authorities to identify both environmentally and potentially suitable locations for wind turbines.

The application of the proposed approach for site selection of solar power plants within the study area is conducted as well. The priority sites for solar power plants are given in Figure 4.27. Approximately 477 $km^2$ of the study area is identified as priority sites for solar power plant constructions. Currently no large scale solar power plants exist in Turkey. This is beneficial for our country because utilization of the proposed decision support tool will give the chance to the authorities to assign permits to economically feasible solar power plants which also have minimum negative impacts on the environment.

Hybrid systems are not applied in Turkey yet. Thus, similar to solar power plants, Turkey will benefit from utilization of the decision support tool for site selection of hybrid systems. Priority sites identified using the proposed approach for hybrid systems of wind and solar energy can be seen in Figure 4.42. Approximately 62 $km^2$ area of the study area is feasible to deploy hybrid wind-solar system which will have higher chances to provide continuous and economically feasible energy and at the same time will sustain the environment. With the identified environmental and economical criteria a total of 477 $km^2$, 6996 $km^2$, and 62 $km^2$ of the study area are identified as priority sites for solar power plants, wind turbines and hybrid systems, respectively. This indicates that even when environmental objectives in addition to the potentials are considered in site selection of solar, wind and hybrid systems, reasonably large areas are identified as suitable locations. Moreover, the proposed methodology allows inclusion of the decision makers' preferences into the site selection process which brings flexibility to the procedure.

In conclusion, the proposed decision support system is used to evaluate economic feasibility together with environmental acceptability for future wind, solar and hybrid energy facilities within the study area. However, the proposed approach is robust; it can easily be modified for additional environmental and economical criteria, for other regions, and other RES. Thus, the proposed decision support system presents a useful tool for site selection of different types of RES as long as associated environmental and economical criteria are carefully identified and necessary data is obtained.

Investigation of EU regulations and revising environmental objectives with respect to these requirements in addition to application of the proposed methodology for other renewable energy sources such as geothermal, hydropower, biomass, and wave are topics for further research.

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