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A multi-criteria GIS analysis for siting of utility-scale photovoltaic solar plants in county Kilkenny, Ireland

Ingrid Piirisaar

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Department of
Physical Geography and Ecosystem Science
Centre for Geographical Information Systems
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

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Ingrid Piirisaar
Master thesis, 30 credits, in Geographical Information Science
Lund University, Sweden

Supervisor:
Dr Helena Borgqvist
Department of Physical Geography and Ecosystems Science
Lund University, Sweden

Abstract

Renewable energy is the keyword for energy industry sector in the world today. Solar energy has a huge potential, able to fulfill increasing energy demand and growing its share of energy sector. Republic of Ireland has one of the lowest solar energy deployment rates in Europe, although climatic conditions have been proved to be acceptable. The purpose of this study was to assess potential sites for utility-scale photovoltaic solar plants in county Kilkenny in south-east Ireland.

The study was based on Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM). Different datasets from Ordnance Survey Ireland, European Environment Agency, Environmental Protection Agency Ireland and The United States Geological Survey were used for the analysis.

Firstly, factors were identified and weighted according to the Analytical Hierarchy Process (AHP), indicating different suitability classes. Secondly, separately constraints were identified to produce a final constraints layer showing the unsuitable locations. Finally, the weighted overlay of factors and the Boolean constraints layers were multiplied together to produce the suitability map for the study area.

The constraints accounted for 85.11% of the study area and 0.67% of the study area was found to fulfill all the required criteria and to be suitable for utility-scale solar plants. Majority of the suitable areas were scattered in the northeast of the county, exemplifying how topography influences incoming solar radiation as the most important factor for solar energy generation.

Keywords: Geography, GIS, MCDM, solar plants, site suitability, Ireland

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1. Introduction

The demand for energy goes hand in hand with global population growth, economic and social development. The changes in the energy industry over the past decades have been considerable. As a result of new and more efficient technologies there are more energy resources available in the world today than in the past, whereby the contribution of renewable energy resources is increasing year by year (World Energy Council, 2013). The continuously growing share of renewable energies is leading transition towards decarbonised and decentralised energy systems (World Energy Council, 2019).

Solar energy is the most abundant and therefore the most promising renewable energy (Darling et. al, 2011). It is the only choice that can satisfy continuously increasing world´s energy demand. Solar energy falls on the surface of the earth at a rate of 120 petawatts (1 petawatt = 1015 watt), meaning that energy recieved in just one day is many times larger than the present energy consumption and would be able to satisfy the whole world`s energy demand for more than 20 years (Chu, 2011).

The photovoltaic (PV) effect was discovered by French physicist A.E.Becquerel in 1839 (Green, 2002; Razykov, 2011). Albert Einstein won the 1921 Nobel Prize in physics for explaining the photoelectric effect (Nobel Media AB, 2017). It took a few more decades until the creation of the first practical silicon solar cell at Bell Labs in 1954 (Chapin et al.,1954).

There are several major directions for solar technology development. For example, photovoltaic systems directly convert the solar energy into electrical energy while concentrated solar power (CSP) systems first convert the solar energy into thermal energy and then further convert it into electrical energy through a thermal engine (Chu,Y., 2011). Whereas photovoltaic systems can be installed almost everywhere, CSP technology incontrary is in the need of the following equally critical components: higher levels of irradiance (typically those of sunbelt countries), access to water (just like a coal plant) and large-scale deployments (STS-Med, 2014). One of the finest ways to harvest the solar power is therefore the photovoltaic technology (Parida et. al, 2011).

Photovoltaic`s possess several fundamental advantages for the energy production. Firstly, photovoltaic converts sunlight directly into electricity without any heat engines to interfere. They are simple designed,thus requiring very little maintenance. As stand-alone systems they are able to give outputs from microwatts to megawatts, making them suitable for a vast array of applications from remote buildings and solar home systems to megawattscale power plants and satellites. (Parida et. al, 2011). The versatility of PV technology is one of its main strengths, i.e. the wide range of sizes and sites, resulting into proximity to electricity demand, in the value of its production profile concentrated during peak-load hours, and its enourmous potential for further cost reduction (EPIA and Greenpeace International, 2011). Other benefits include high reliability and no moving parts (World Energy Council, 2013; Malik et. al, 2013), quick installation and dismantling (World Energy Council, 2013) and a long lifetime of more than 20 years (Malik et. al, 2013). Large-scale photovoltaic systems in particular play a very important role in the reduction of the greenhouse gas emissions and in the reuse of marginal land cover (Castillo et. al, 2016).

Despite the fact that grid-connected PV still represent a tiny fraction of circa 14 GW globally of the overall worldwide electricity production, it is certain that in the coming era of renewable energy photovoltaics will represent a significant share of the new energy sector (Darling et. al, 2011). PV has already become a real business and is clearly the fastest growing electricity source over the past years (Kazmerski, 2006) growing at very high rates 30-40% per year (Razykov et. al, 2011).

According to the EU´s Renewable Energy Directive (2009/28/EC) 20% of the total energy consumption has to come from renewable resources by 2020 (Perpiña et. al, 2016; European Commission 2009). At least a 27% share of renewable energy consumption has been agreed for 2030 (European Commission, 2015a). The shares of renewable energy sources (RES) at Memeber State level vary greatly, ranging from 52.1% in Sweden to 3.6% in Luxembourg (European Environment Agency, 2016b).

In 2015 Republic of Ireland reached 9.1% of it`s 16% overall renewable energy target of gross final consumption to come from renewables for 2020. Total installed renewable energy capacity reached 2787 MW. Wind energy as the largest supplier of renewable energy accounted for an installed capacity of 2440 MW and solar energy as last with just 2 MW installed capacity, indicating that solar energy is almost non-existant in the renewable energies fuel mix (SEAI, 2016).

Solar energy can be utilized in a number of practical ways. Mostly, it is used to produce electricity or heat. Additionally, it can be utilised in a wide variety of industry sectors to operate engines, lights and other equipment (Mekhilef et.al, 2011). It has also been applied in agricultural sector and in dairy farms which might be of particular interest to Ireland, e.g. for water pumping, cooling of milk etc.(Bey et.al, 2016).

Incontrary to the misconception Ireland recieves annually between 910 – 1100 kWh/m^2 solar radiation (Sustainable Energy Authority of Ireland,2011), comparable to the Europe`s largest solar power market Germany`s average annual 1055 kWh/m^2 (Deutsche Wetterdienste,2012). The highest annual mean global radiation 344 210 joules/cm^2 (i.e. ca 956 kWh/m^2) on mainland is found south-east in county Kilkenny (The Irish Meteorological Service Online, 2015).

The study is based on Geographical Information System (GIS) and Multi-Criteria Decision Making (MCDM). GIS is a digital database management system designed to manage large volumes of spatial data from various sources and therefore ideal for site selection studies (Siddiqui et al, 1996). GIS consists of following components: spatial database, analytical functionality and visualition capability (Huang et al., 2011). The ability to query, analyse and present information in a number of ways can significantly simplify the complex process of discovering the most suitable sites (Sylvester, 2018).

MCDM has been found to be a useful approach in situations where many potential criteria must be considered (Önüt and Soner, 2008). A choice must be made among multiple, often conflicting criteria and the final solution is dependent on the preferences of the decision-maker (Pohekar and Ramachandran, 2004). Malczewski (2006) described MCDM as a collection of techniques for structuring decision problems, and designing, evaluating and prioritising alternative decisions. MCDM breaks the problem into smaller pieces, makes sure that all available criteria is taken into consideration and ensures the quality of the decision process. Altogether, MCDM helps to structure the decision process and to limit and evaluate the possible alternatives, helping the decision-maker in the search for the best available options.

Since location selection is a complex problem and usually involves several steps and criteria that need to be evaluated, both GIS and MCDM will be applied to determine the most favorable locations. The combination of GIS tools and MCDM methods enables to integrate spatial datasets with a large number of value judgements (Malczewski,2006). GIS together with MCDM methods has emerged as a preferred technique in the site selection (Al Garni and Awasthi, 2017).

The aim of the study is to present, apply and evaluate GIS based MCDM methods to assess county Kilkenny in Ireland in terms of potential sites for utility-scale photovoltaic solar plants. The study attempts to address the following question: Is it possible to identify preferred locations for utility-scale solar plants development in county Kilkenny?

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2. Background

2.1 Solar power

Solar power is widely recognised as an important sustainable energy source.Since 2000, solar power capacity worldwide has increased more than 100 times, with 178 391 MW global solar PV capacity installed at the end of 2014 (Solar Power Europe, 2015). Cumulative installed PV capacity has grown at an average rate of 49% per year in the years 2003 - 2013 (IEA, 2014).

Europe`s share in global solar power is on decline since solar PV is being more and more deployed all over the world. In 2010 Europe dominated the global solar PV grid-connected market overwhelmingly with around 75% share, left with just 16% annual global market share in 2015 (SolarPower Europe, 2016b) (Figure 1).

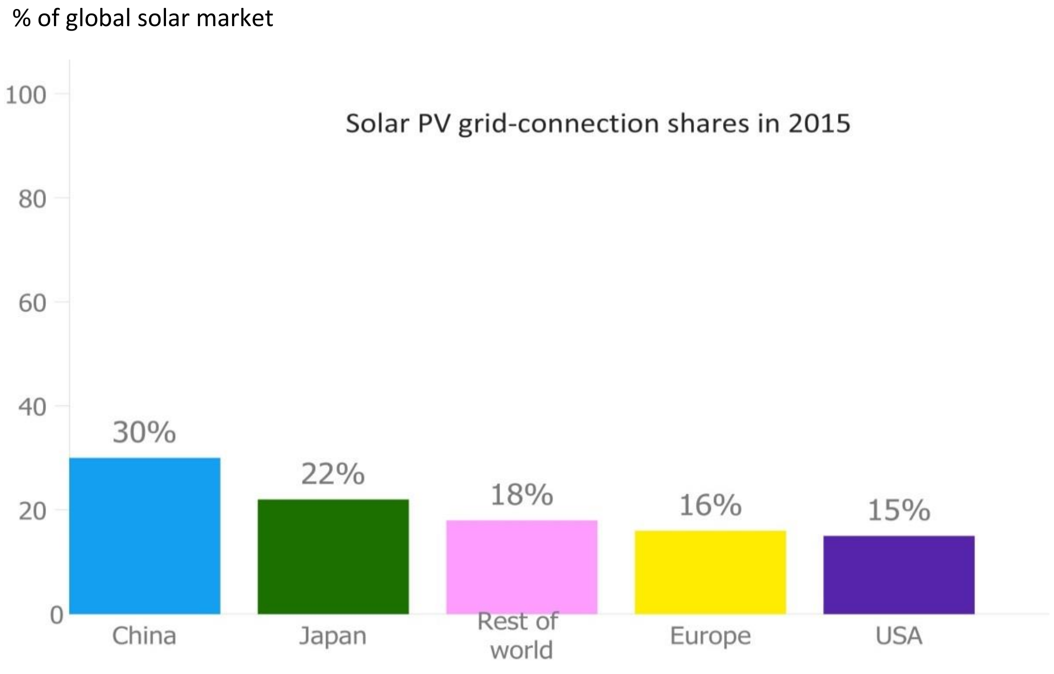

Figure 1: European solar PV grid-connection shares in 2015 compared to other regions (after SolarPower Europe, 2016b).

These developments over the years can be explained by the time required for adopting a new technology, as no innovations spread instantaneously (Grübler,1996). The barriers and drivers influencing the use of solar energy differ geographically (Palm,2017),therefore the diffusion of PV technology as of any other technological innovation is also a spatial phenomenon (Grübler,1996). Due to the late starter benefit, being able to learn from the experiences made in this field, the development time is much shorter in the regions starting the adoption process at a later time than it used to be in the core areas (Grübler,1996). Farmer and Lafond (2016) made a forecast for solar PV technology and predicted continuous significant growth for solar PV in the near future.

Europe still remains the world´s most solarised continent (Solar Power Europe, 2016b). Solar PV meets 3.5% of the overall European electricity demand and reached more than 7% of the electricity demand in 3 countries: Italy, Germany and Greece (Solar Power Europe, 2015).

United Kingdom, Germany and France are the top three leading solar power markets in Europe (Solar Power Europe, 2016a) (Figure 2).

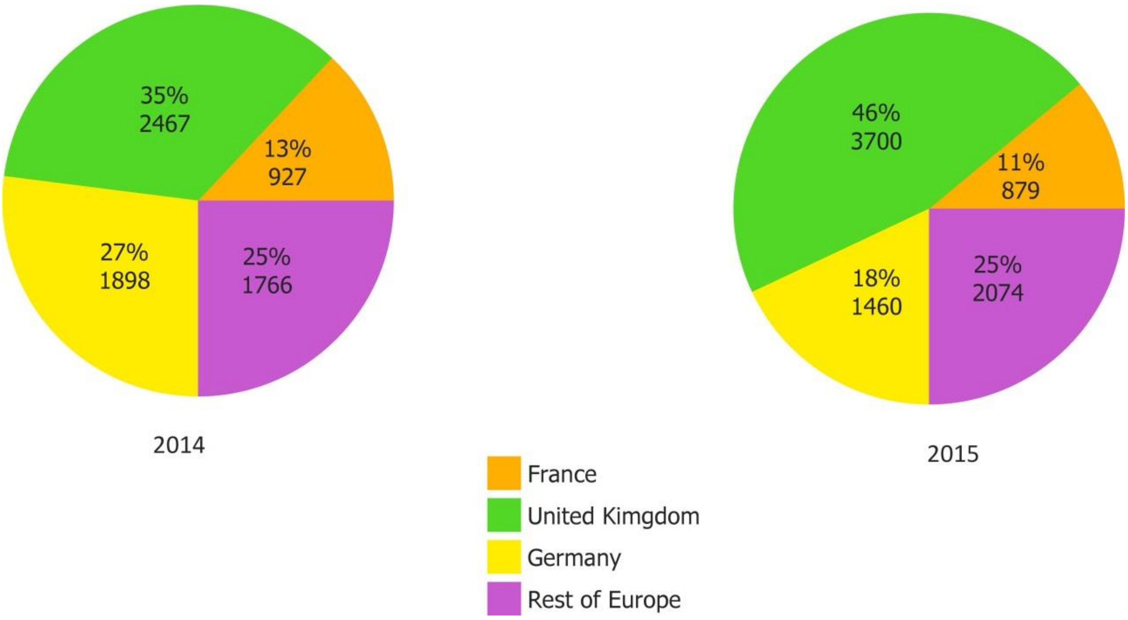

Figure 2: European solar market share (MW) in 2014 and 2015 (after Solar Power Europe, 2016a).

2.2 Solar power plants

2.2.1 PV-systems

PV systems continue to be built at all scales, reaching from just a few kilowatts to hundreds of megawatts. On one side small domestic off-grid systems far from electricity networks versus utility scale plants of over 100 megawatt capacity (IEA 2014).

Main types of PV systems:

- *Off-grid PV system*: off-grid systems operate in a stand-alone mode and are usually used in remote rural areas that are not easily accessible or have no access to an electric grid. These systems consist of PV modules, batteries,a charge controller and additionally an inverter if AC electricity is needed. Rechargable batteries are required for storing the energy for the periods when sun is not shining or when the PV system cannot meet the demand. A charge controller regulates the power and prevents the batteries from overcharging (Kalogirou,2009) (Figure 3).

Figure 3: 6.7MW off-grid Weipa solar plant, Australia. (Source: Australian Renewable Energy Agency (ARENA), 2014. Public domain image.)

- *Grid-connected PV system*: connected to the local electricity network. Electricity flows back and forth to and from the grid.Excess electricity can be fed back into the grid and sold, whereas during energy shortfall power can be bought back from the network. In this case the grid is acting as an energy system, meaning battery storage is not necessary (Kalogirou,2009) (Figure 4).

Figure 4: 11 MW grid-connected Serpa Solar Park, Portugal. (Source: Ceinturion,2006. Licensed under CC BY-SA 3.0 license via Wikimedia Commons.)

2.3 Solar power planning

2.3.1 Performance aspects

Efficiency of PV systems is affected by multiple external factors. Starting from the most important condition, solar radiation determines the amount of energy generated. Sunlight is the source of solar energy and high enough sunlight levels are required for the solar farms to be viable.

Secondly, solar photovoltaic output depends on PV panel`s orientation and tilt angle, both changing the amount of solar energy recieved by the surface of the PV panel. Additionally tracking systems considerably increase solar plant`s efficieny (Kacira et. al, 2004).

2.3.2 Environmental aspects

Solar PV energy is considered to have relatively low environmental risks. Potential negative impacts include habitat loss, habitat fragmentation/modification and disruption to wildlife (disturbance/displacement of species) caused through the site activities (BirdLife International, 2015). Habitat fragmentation is mainly caused by physical barriers such as fences, influencing free animal movement and leading to more limited resources (The Wildlife Society, 2016). Whereas it is advisable to minimise the use and height of the security fencing (BRE National Solar Centre,2013), solar farms are usually fenced above head height for security reasons (BHS,2015). Fences may have small openings at the base of the fence to allow small animals to access the facilities (US-DOE,2009). The main impact is therefore caused due to land occupation by the power plant itself (Fthenakis et. al, 2011).

An environmental impact report for 550 MW Topaz Solar Farm photovoltaic project in California,USA (US-DOE,2011) found potential for following environmental impacts:

- Wildlife displacement from the site.
- Preventing wildlife to use the site for foraging, breeding, wintering and shelter.
- Possible injury to ground-or shrub-nesting birds, small animals and slower-moving species.
- Soil disturbance and possible plant removal during construction phase may cause the loss of soil nutrients and establish/increase the spread of invasive weeds.
- Visual Impact – the alteration of the rural and agricultural character of the place.
- Altered soil temparatures, moisture regime and shading under PV arrays that could change habitat suitability for certain species.

According to the same report (US-DOE,2011) in the long term, after the the contruction activities, a passive solar facility could improve the habitat quality.

Figure 5: Kobern-Gondorf facility solar facility, in Germany, is used as a nature reserve for endangered species of flora and fauna. (Source: BRE National Solar Center,2013.Reproduced with permission from Mrs Chris Coonick, BRE National Solar Center.)

The effects of solar farms can likewise prove to be positive and benefit local wildlife, e.g. construction of suitable habitats for endemic species while eliminating invasive or overpopulating species, the exclusion of recreational off-highway vehicles, increased field surveys and monitoring of the ecosystem (Fthenakis et. al, 2011) (Figure 5). Significant beneficial impacts to human health and well-being have been proved to be true. Emissions of hazardous chemicals like mercury, cadmium and others,including particulates, are considerably smaller than those from traditional power (Turney et.al, 2011).

2.3.3 Economic aspects

PV deployment has been very fast, making it the dominant solar electricity technology due to its rapid expansion and decreasing costs (IEA 2014).

Over the last few years PV module manufacturing industry has shifted from Europe to Asia, mostly to China and Chinese Taipei (IEA 2014), resulting in the more affordable cost of the modules. The costs for solar PV have fallen by 80% between 2008 – 2014 and are expected to keep dropping. Consequently, commercial solar power reached grid parity in Italy, Germany and Spain in 2013, i.e. power is produced at a levelised cost of electricity (LCOE) that is less than or equal to the price of purchasing power from the electricity grid. With technology improvements the efficiency and performance of the modules is rising, the ability to convert sunlight into electricity has improved ca 3% - 4.5% per year for the last ten years (IRENA,2014).

2.3.4 Social aspects

Solar energy is one of the most popular and socially acceptable among renewable technlogies. According to UK Department of Energy & Climate Change public attitude tracking surveys solar power keeps the first place as the most supported renewable energy development (DECC 2016; Solar Power Portal 2015). Similarly, European Commission`s public opinion analysis has found EU citizens are with 80% most in favour of solar energy, followed by wind and hydroelectric energy (EC 2006). However, still in many cases the availability of suitable renewable energy sites is being questioned by the local society opposition (Kaldellis et.al, 2012) as a form of place-protective action to new developments near homes and communities described as NIMBY (Not In My Back Yard) syndrome (Devine-Wright, 2009).

Some of the key aspects influencing peoples opinion on solar energy are e.g (ISEA,2014):

- Landscape Visual Impact. Well selected sites could be easily made invisible and hidden behind hedgerows.
- Minimal impact on the environment. No emissions to the air, soil and water. No noise.
- Agricultural activities such as grazing may continue between and underneath the PV modules.

- Enhanced biodiversity and regeneration of agricultural land.
- Diversification of farming income.
- Easily reversible. Can be installed and taken down very quickly.

2.3.5 Legal aspects

Solar is the only renewable energy in Ireland that does not qualify for Renewable Energy Feed-In-Tariffs (REFIT) or any other financial incentives. The REFIT schemes stimulate the development of renewable electricity generation and provide price certainty,guaranteeing a fixed price for each unit of electricity exported to the grid (SEAI,2017). The Irish Solar Energy Association (2014) called for Government to introduce a support mechanism for solar energy to help to ensure 2020 renewable targets will be met and to secure the country`s energy future.

Due to absence of support frameworks only some existing stand-alone commercial and domestic installations are in place. No statistics are available for these installations (SEAI,2015b). State owned electricity company ESB Networks is responsible for the electricity transmission system and grid connections in the Republic of Ireland. According to ESB Networks statistic (Codd, 2016) only 0.05 MW solar PV has been connected to the grid.

One of the reasons why solar energy has been ignored is the the strong focus on wind energy. Ireland has one of the best wind resources in Europe (SEAI,2003). Consequently, they are trying to make full use of it. Wind energy has been the dominant renewable energy since 2008, reaching 80.2% of renewable electricity contribution to gross electricity consumption in 2014 (SEAI,2015a). Much poorer solar resource has long been used as an excuse for not developing solar power. Recent studies have shown there is enough sun in Ireland for the successful deployment of solar PV (ISEA,2014; KPMG,2015).

In order to promote solar energy Irish Government should adapt effective support mechanism for solar PV similar to other European Union countries.

2.3.6 Land use aspects

Land use is one of the most important factors in the site planning process. It is often a challenge to find suitable and effective areas for solar farms without causing any ecological harm (Munsell,2013). Ideally, solar projects should utilize brownfields, previously developed land and other low value and unused land (BRE,2013). Although solar farms can be built on agricultural land, it is at the same time important to protect the farmland to ensure it is used for growing crops, not forcing the farming land out of production.

It is a common belief that renewable energies are widely scattered and therefore not easy to harvest, requiring more land resources than conventional energy resources. Fthenakis and Kim (2009) analysed land requirements during the life cycles of conventional and renewable energy options. The photovoltaic (PV) cycle was found to require the least amount of land and cause the least disturbance to the land among the renewables. Similarly, in most cases ground-mounted PV systems transform less land than coal-fuel cycle coupled with surface mining. As distinct from conventional fuel cycles, PV use the land statically, there is no need for further extraction of resources once the infrastructure is constructed.

Turney et.al 2011 compared land use intensity for the life-cycles of large-scale solar plants to coal-fired power plants. Solar power plants are designed approximately for 30+ years of operation. The land transformation per capacity remains unchanged while the land occupation per energy created decreases with age of the solar plant. The coal power life cycle requires mining. A 30-year old photovoltaic power plant was found to occupy ca 15% less land than a coal power plant at the same age. As the power plants age, the land use intensity of photovoltaic power becomes significantly lower than that of coal power.

2.4 Solar Analyst

Solar Analyst extension for ArcGIS has been designed by Fu and Rich (1999) for modeling solar radiation at landscape scales. Insolation can vary strongly already within short distances in consequence of topograhical features. Elevation, slope, aspect and shadows cast by topographic features all influence the distribution of incoming solar radiation.Therefore insolation maps are calculated using digital elevation models (DEMs) as input, based on an advanced viewshed algorithm. Output can be computed for any time period – daily, biweekly, monthly, yearly (Fu and Rich,1999).

Solar Analyst enables the calculation of direct, diffuse and global insolation separately. Direct radiation is intercepted as a direct line from the sun to the surface. Diffuse radiation has been scattered in the atmosphere, caused by clouds, dust and other atmospheric constituents (ESRI:ArcGIS Resource Center, 2014f). Global radiation ($Global_{tot)}$) is calclulated as the sum of direct ($Dir_{tot)}$) and diffuse radiation ($Dif_{tot)}$) (ESRI:ArcGIS Resource Center, 2014d):

$$Global_{tot} = Dir_{tot} + Dif_{tot} \qquad \text{(Eq.1)}$$

Charabi and Gastli (2011) used Solar Analyst module to calculate the total solar radiation map for research on solar energy resource assessment in Oman. The modules`s capabality to include slope, hill shade and aspect, as well as possibility to modify the coefficient of the atmospheric transmissivity, was stressed by the researchers. Effat (2013) used ESRI Solar Analyst for solar radiation mapping to investigate optimal site locations for solar energy plants in Ismailia Governorate, Egypt. Munsell (2013) analysed the solar potential of closed landfills in California,USA. He estimated solar irradiance with the help of Area Solar Radiation tool, producing a raster representing insolation in watt hours per square meter (WH/m2) that reached each cell of the elevation over a year.

Solar Analyst has come to be one of the most popular solar radiation modeling tools and has been widely used in solar power planning processes.

3. Theory

3.1 GIS as solar power planning tool

GIS enables to arrange information as a set of maps, with each layer displaying certain characteristics of the region (Foote and Lynch,1995) (Figure 6).

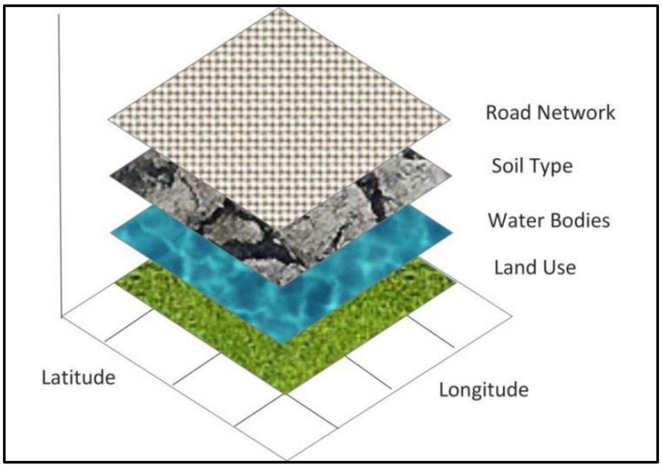

Figure 6: Overlay of different map layers (after Foote and Lynch,1995).

Different layers can be compared and analysed in any desired combination. Additionally, single areas can be separated from their surroundings by cutting from the larger map (Foote and Lynch,1995) (Figure 7)

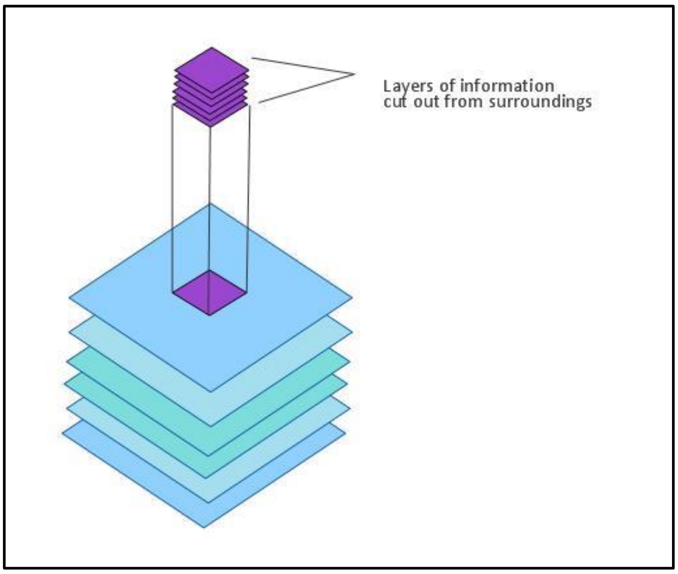

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Figure 7: An example of separating single locations from the surroundings (after Foote and Lynch,1995).

Information can be used selectively, e.g. combining two or more layers and then creating a new layer. The process of combining and transforming information from different raster layers is called map algebra (Foote and Lynch,1995) (Figure 8). In its simplest form it involves adding, subtracting, multiplying or dividing information. More complex expressions can include the use of parentheses and multiple operators in the same statement (ESRI:ArcGIS Resource Center, 2014e).

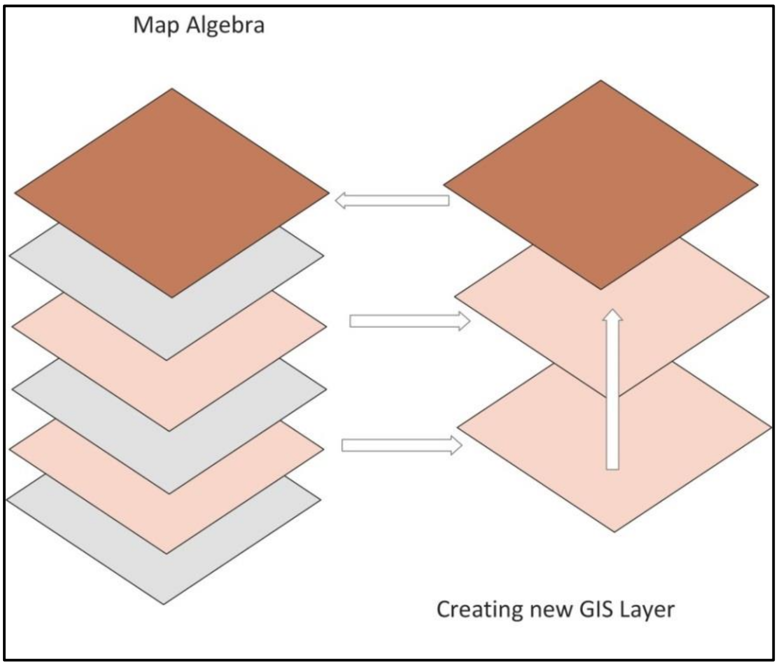

Figure 8: Combining and transforming GIS data raster layers (after Foote and Lynch,1995).

Environmental management is directly linked to the geographic context and therefore has been the prime motivator of developments in GIS throughout its history. GIS has become to be an essential tool in nowadays environmental managemet, it plays a dominant role in the development of environmental policy and in environmental decion making (Goodchild, 2003).

GIS have been used in multiple studies in order to determine the optimal sites for solar PV (e.g. Brewer et al.,2015; Carrion et al., 2008a; Charabi and Gastli, 2011; Effat, 2013; Georgiou and Skarlatos, 2016; Janke, 2010; Sánchez-Lozano et al.,2013; Uyan,2013; Watson and Hudson,2015). Hence, GIS have been proved to be useful for assessing potential solar plant locations.

3.2 Multi – Criteria Decision Making

MCDM methods provide us a set of tools for spatial decision making processes, in order to help to find the solutions for multiple choice alternatives. Since GIS deals with evaluating locational choice alternatives on the basis of suitability criteria, much effort has been made in integrating MCDM with GIS software (Jankowski et al.,2001).

As stated by Beinat (1997) the aims of MCDM are following:

- to aid decision-makers to be consistent with fixed "general" objectives;

- to use representative data and transparent assessment procedures;

- to help the accomplishment of decisional processes, focusing on increasing it´s efficiency.

MCDM has a number of different techniques, all with their own characteristics and calculation methods but the final choice of the method always depends on the context (Aragonés-Beltrán et al.,2014).

The most common multi-criteria evaluation approaches involve Boolean variables called constraints (true/false) and fully continuous variables called factors (Eastman, 2005). Constraints serve to define areas that are not deemed to be suitable, combined by some combination of intersection (logical AND) or union (logical OR) operators. The AND operator excludes a region from the result if any single criterion fails to exceed it´s threshold (Eastman, 2005). E.g. all areas within 2 km radius from national parks may be deemed not suitable for real estate development but at the same time the perfect location should be as close to the roads as possible. Combining both national parks and roads datasets by using AND operator excludes all areas within 2 km radius from national parks from the results even though these may be close to roads. The OR operator includes a region in the result even if only one criterion meets the set requirements (Eastman, 2005), i.e. areas close to roads but within 2 km radius from national parks would be shown in the resulting layer.

Quantitative criteria such as distance from roads are evaluated as fully continuous variables, expressing varying degrees of suitability according to a special numeric scale (e.g. 0–1, 0–100, 0–255, etc.). The process of converting data to a numeric scale is called standardisation (Eastman, 2005).

Standardised factors are combined by applying a weight to each, whereby the weights are determined by using the selected MCDM method. The result may then be multiplied (i.e. intersected) by Boolean constraints that may apply (Eastman, 2005), e.g. national parks Boolean constraints layer multiplied by distance from roads weighted factors layer.

3.2.1 Analytical Hierarchy Process

Among various MCDM methods, Analytic Hierarchy Process (AHP) developed by Saaty (1977), has been chosen for this study purposes as one of the preferred methods for location selection. According to Linkov et al. (2007) AHP is „a systematic pairwise comparision of alternatives with respect to each criterion … based on a special ratio scale : for a given criterion, alternative *i* is preferred to alternative *j* with the strength of preference given by $a_{ij}=s$, $1 \leq s \leq 9$, correspondingly, $a_{ji}=1/s$.“

Wang et al.(2010) described the workflow of AHP in following steps:

- hierarchical framework;

- paired comparision matrix;

- computation of consistency ratio;

- calculation of relative weights of criteria.

The use of pairwise comparisions instead of direct weights or value functions is the distinctive feature of AHP (Linkov and Moberg,2012) and has been used long time before in psychology since it is thought to be easier and more accurate to give an opinion on just two alternatives than simultaneously on all the alternatives (Ishizaka and Labib,2011).

Measurments of concepts like politics, social values etc change from one situation to another and cannot be captured on Cartesian coordinate system (Saaty,2008). As Saaty (2008) argues, our understanding and judgments are the most important determinants of why we want to measure something in the first place. Understanding is needed to make judgments as the importance of each criterion is based on subjective human judgements.

A weight for each criterion is generated by comparing the pairs of criteria. A value of 1 expresses „equal importance“ and a value of 9 expresses „extreme importance“ over another factor in the comparision matrix (Saaty,1997) (Table 1).

Table 1: Saaty`s scale in the pair-wise comparision process (after Saaty, 1977).

Definition	*Importance*
Equal importance	1
Weak importance of one over another	3
Essential or strong importance	5
Demonstrated importance	7
Absolute importance	9
Intermediate values between two adjacent judgments	2,4,6,8

A Consistancy Index (CI) is calculated (Eq.2):

$$CI = (\lambda max - n) / (n - 1) \qquad \text{(Eq.2)}$$

where λmax is representing the maximum eigenvalue of the comparision matrix.

Perfectly consistent pairwise comparisions should obtain CI=0, but the AHP tolerates inconsistencies of small values. Finally, Consistency Ratio (CR) is calculated to assess the consistency (Eq.3):

$$CR = CI / RI \qquad \text{(Eq.3)}$$

where RI is the random consistency index.

If CR < 0.10, the rankings are considered satisfactory consistent. If CR ≥ 0.10, comparisions should be revised since they are not considered to be sufficiently consistent (Bhushan and Rai,2004).

The main advantage of the AHP is the possibility to include qualitative values logically in the analysis (Andersen,2000; Choudhary and Shankar, 2012; Ishizaka and Labib, 2011). The fact that both qualitative and quantitative data can be converted into a common scale encourages participation of all stakeholders and enables to include social factors and public opinions in the analysis. The other strengths are the fact that consistency can be measured and the use of hierarchical structure to present the decision problem (Andersen,2000; Choudhary and Shankar,2012; Ishizaka and Labib, 2011). The possibility to check consistency ensures pairwise comparisions are consistent and helps to avoid any unintentional mistakes.

Some of the drawbacks of the AHP are the large number of pairwise comparisions needed as the number of alternatives increases (Andersen,2000; Choudhary and Shankar,2012),the critic regarding the measurment scale (Lootsma,1993) and calculating the final scores via aggregation (Ishizaka and Labib, 2011; Lootsma,1993). The latter can lead to compensation between good scores on some criteria and bad scores on other criteria (Choudhary and Shankar,2012), i.e. low performance on one criteria may be balanced by high performance on other criteria.

Regardless of aforementioned critic, Pohekar and Ramachandran (2004) found AHP to be the most popular MCDM technique in sustainable energy planning.

Because of it´s flexibility to include both quantitative and qualitative criteria (Choudhary and Shankar,2012), AHP has been widely accepted and has been applied in a number of fields, for example in site selection (Carrion et al.,2008a; Effat,2013; Georgiou and Skarlatos,2016; Sánchez-Lozano et al.,2013; Tahri et al.,2015; Uyan,2013; Watson and Hudson,2015; Önüt et al.,2009) selection of recycling technology (Hsu et al.,2010), supplier selection (Wang et al., 2010), selection of investment projects (Aragonés-Beltrán et al.,2014), staff recruitment (Khosla et al., 2009).

Sensitivity analysis plays an important role in the AHP. The data in MCDM problems are often changeable and the judgments subjective (Simanaviciene and Ustinovichius,2010), therefore it is important to perform a sensitivity analysis to test the stability of the rankings under varying weights (Chang et. al, 2007). Changes of the priorities can be observed by increasing or decreasing the weights of individual criteria. If the sensitivity analysis is found to be highly sensitive even to small changes, the current weights should be previewed and it is recommended to include additional decision criteria (Chang et. al, 2007).

3.3 GIS solar power planning studies

The following chapter aims to give a brief overview about previous related works and studies on PV site suitability.

The techniques used in solar site selection range from AHP and Multicriteria Analysis (MCA) (Effat, 2013; Tahri et al., 2015; Uyan, 2013; Watson and Hudson, 2015), Fuzzy Logic Ordered Weight Averaging (FLOWA) (Charabi and Gastli, 2011), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Sánchez-Lozano et al.,2013) to including public acceptance survey data into analysis (Brewer et al., 2015) (Table 2).

Table 2: Main techniques used in solar site selection.

Author	*Article*	*Methodology*
Brewer et al. (2015)	Using GIS analytics and social preference data to evaluate utility-scale solar power site suitability.	GIS, public attitudes data
Carrion et al (2008a)	Environmental decision-support systems (EDSS) for evaluating the carrying capacity of land areas: Optimal site selection for grid-connected photovoltaic power plants.	GIS, EDSS (including MCA and AHP)
Charabi and Gastli (2011)	PV site suitability analysis using GIS-based spatial fuzzy multi-criteria evaluation.	GIS, MCA, FLOWA
Effat (2013)	Selection of Potential Sites for Solar Energy Farms in Ismailia Governorate, Egypt using Shuttle Radar Topography Mission (SRTM) and Multicriteria Analysis.	Spatial Multicriteria Evaluation (SMCE), AHP
Georgiou and Skarlatos (2016)	Optimal site selection for sitting a solar park using multi-criteria decision analysis and geographical information systems.	GIS, MCA, AHP
Sánchez-Lozano et al.(2013)	Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods for the evaluation of solar farms locations: Case study in south-eastern Spain.	GIS, MCDM, AHP, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
Tahri et al. (2015)	The evaluation of solar farm locations applying Geographic Information System and Multi-Criteria Decision-Making methods: Case study in southern Morocco.	GIS, MCDM, AHP
Uyan (2013)	GIS-based solar farms site selection using analytic hierarchy process in Karapinar region, Konya/Turkey.	GIS, MCA, AHP
Watson and Hudson (2015)	Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation.	GIS, MCDM, AHP

The attributes analysed in the assessment of new sites vary from study to study, although certain criteria like access to roads and whether slope or aspect (or both) are adopted by all researchers. Some of the more rare and interesting factors taken into account are visual impact (Carrion et al., 2008a; Georgiou and Skarlatos, 2016; Watson and Hudson, 2015), sand and dust risk (Charabi and Gastli, 2011) and land surface temperature (Tahri et al., 2015).

A variety of researches with different methods have been presented. As of the above, the choice of methodology and criteria ultimately depends on the location and the intended goal of the research.

Watson and Hudson (2015) used a GIS-assisted multi-criteria evaluation method to assess suitability for wind and solar developments in southern England. The study was conducted in three stages. First, a binary constraint layer was created to exclude unsuitable locations and a factor layer developed to indicate high and low suitability for solar farm development. AHP was applied to produce the weightings for factor variables from the pairwise comparisions. Secondly, suitability layers for the whole region were created. Last, a sensitivity analysis was performed to check the reliability of the suitability model. The results revealed high suitability for solar farm developments. This study is particularly important in relation to Ireland because it shows the potential of solar energy in the closest neighbouring country and offers an example of how and to what extent solar farms could be deployed.

Sánchez-Lozano et al.(2013) applied MCDM methods to evaluate optimal solar farm locations in the area of Cartagena in Spain. The region has one of the highest solar radiation levels in Spain and is ranked fourth nationally according to the generated PV solar power values. Analysis was conducted using AHP for determining the weights of factors and the assessment of the alternatives carried out through TOPSIS method. According to the TOPSIS method, the chosen alternative should have the shortest distance from the Positive Ideal Solution (PIS) and the farthest from the Negative Ideal Solution (NIS). The method consists of following steps: creation of the evaluation matrix, normalisation of the matrix, calculation of the weights, determination of the best and worst alternative, calculation of the separation measures, calculation of the relative closeness to the ideal solution and ranking the preference order. Apart from the common factors included in solar site selections, Sánchez-Lozano et al.(2013) also considered mean annual temperature and agrological soil capacity in their analysis. The gvSIG software was used for developing the project and processing the data. All the collected data and cadastral information was used for the creation of the database. The final database contains all the suitable plots with relevant attribute data. The study identified the most favorable locations for solar plants and found the area of Cartagena to have a high acceptance rate to implement solar energy and to be an optimal area to install solar PV plants.

Tahri et al. (2015) asessed solar farm suitability in Morocco. In 2009, the Moroccan Agency for Solar Energy (MASEN) launched the development of the 500 MW Ouarzazate plant for PV and CSP technologies. As no published data existed regarding the suitability of the location of the Ouarzazate PV farms, this region was chosen for the case study to evaluate already existing and potential sites. The study combined MCDM and AHP methods. Four criteria were used in the selection process: location, orography, land use and climate. Climate was found to be the most important factor in the selection process since it defines the potential electricity production, followed by orography, land use and location criteria. The analysis showed high suitability for implementing solar power generation projects whereby the majority of most suitable sites were found to be on flat grounds and oriented towards the south.

4. Data and methods

4.1 Study area

The study area covers county Kilkenny in south-east part of Ireland (Figure 9). The county occupies an area of 2073 km2 (Central Statisctis Office Ireland, 2010) and had the population of 99 232 people in 2016 (Central Statisctis Office Ireland, 2016). The main city is the city of Kilkenny at the center of the county and the towns Ballyragget, Castlecomer, Graiguenamanagh, Mooncoin, Callan and Thomastown.

The river Nore runs through the county and the rivers Suir and Barrow run across the borders with the neighbouring counties. The main land cover category is grassland as in the rest of country (Central Statistics Office Ireland, 2012). The county is hilly but relatively low compared to the rest of the country, with the highest peak Brandon Hill at 515 metres above the sea level. The centre of the county is relatively flat and covered by highly fertail lands, highlands located in the North-East, the North-West and the South (Kilkenny County Council, 2012).

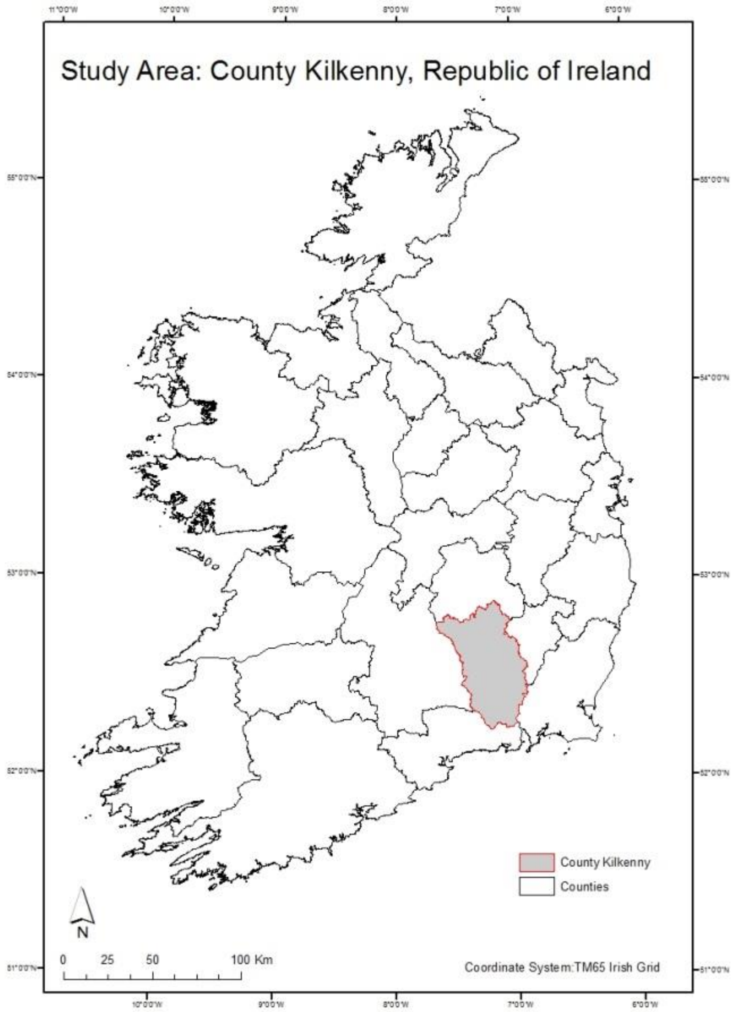

Figure 9: Study area in County Kilkenny, Ireland.

The mean annual solar radiation between 1979 – 2008 was 344 210 joules/cm^2 (i.e. ca 956 kWh/m^2) (The Irish Meteorological Service Online, 2015) (Figure 10), making Kilkenny the county with highest solar radiation on the mainland. Watson and Hudson (2015) analysed solar farms suitability in South Central England with irradiation values of approximately 1000 kWh/m2 per year which are comparable to the study area of county Kilkenny.

Global solar radiation is the sum of direct, diffuse and ground-reflected radiation (NREL, 1992).

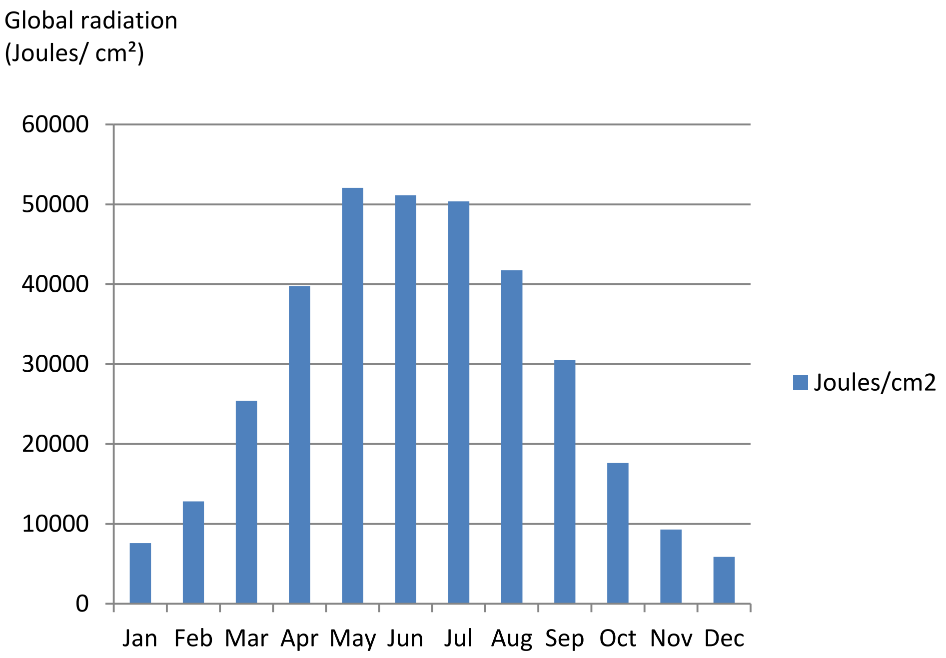

Figure 10: Mean Global Radiation in Joules/ cm², Kilkenny 1979 – 2008 (after The Irish Meteorological Service Online, 2015).

The region was chosen based on sunshine and solar radiation data, i.e. solar energy potential. County Kilkenny can serve as an example for solar power development in Ireland.

4.2. Data

Freely available data from Ordnance Survey Ireland, Environmental Protection Agency Ireland, European Environment Agency and The United States Geological Survey websites have been used in this study (Table 3).

Table 3: Datasets used in the study.

Data	*Issue Date*	*Raster Resolution*	*Source*	*Type*
Counties	26.08.2015	N/A	Ordnance Survey Ireland (2016d)	Shapefile Feature Class
Built-up area points	07.08.2015	N/A	Ordnance Survey Ireland (2016a)	Shapefile Feature Class
Heritage	07.08.2015	N/A	Ordnance Survey Ireland (2016b)	Shapefile Feature Class
Rail network	07.08.2015	N/A	Ordnance Survey Ireland (2016e)	Shapefile Feature Class
Roads	07.08.2015	N/A	Ordnance Survey Ireland (2016f)	Shapefile Feature Class
Natura 2000 (end 2014)	20.05.2015	N/A	European Environment Agency (2016a)	Shapefile Feature Class
CORINE landcover	01.11.2012	N/A	Environmental Protection Agency Ireland (2016)	Shapefile Feature Class
DEM	18.09.2012	3 arc-second (90 m)	The United States Geological Survey (2016)	Raster

Due to unavailability of transmission lines data to the study area, this criterion has not been considered. According to Charabi and Gastli (2011) the omission of transmission lines data enables to identify potential routes for future power lines development nearby most suitable PV farm locations.

All datasets extents are clipped to the study area and projected to Irish National Grid (TM65_Irish_Grid).

The DEM files are provided as 16-bit signed integer data in a simple binary raster. The two tiles N52W007.hgt and N52W008.hgt are converted into ESRI grid format. Thereafter they are merged together and finally, the DEM are re-projected to Irish National Grid and clipped to the study area.

Slope in percentages and aspect are calculated from the DEM. Also, DEM serves as input for insolation calculations using Solar Analyst.

4.3. Methodology

MCDM and AHP have have been adopted for this study purposes.

Due to the absence of planning policy and national guidelines for solar farm developments in the Republic of Ireland, the criteria used in this study are based on relevant works and expert opinions in the field of PV site suitability assessment from other countries (Table 4).

Table 4: Set of rules from previous studies.

Variable	*Criteria*	*Reference*
Slope	< 5%	Brewer et al.,2015; Charabi and Gastli, 2011
Aspect	SE - SW facing	Effat,2013; Georgiou and Skarlatos,2016; Tahri et al., 2015; Watson and Hudson, 2015
Heritage	> 1000 m buffer	Watson and Hudson, 2015
Protection areas	> 1000 m buffer	Watson and Hudson, 2015
Urban areas	> 500 m buffer	Uyan,2013; Watson and Hudson, 2015
Roads	> 100 m buffer	Uyan,2013

A hierarchical model demonstrates how the criteria are constructed (Figure 11).

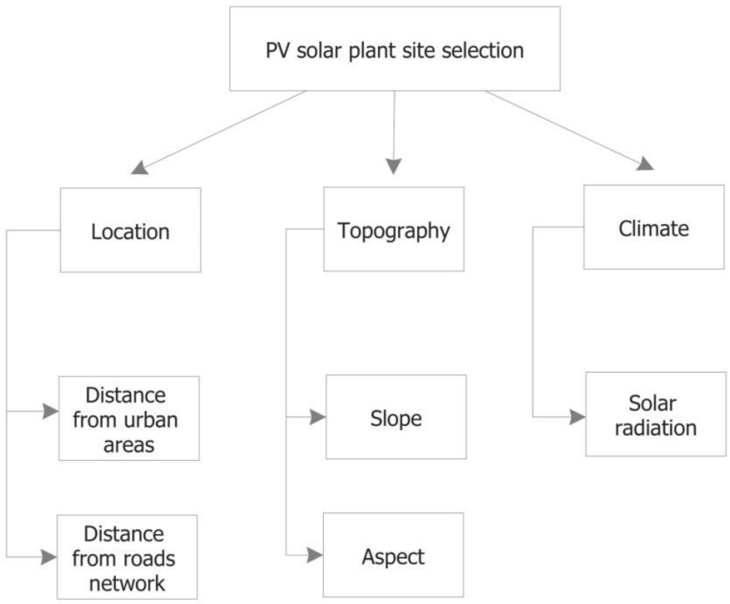

Figure 11:Hierarchy tree for the selection of PV solar plant.

Calculations were made using AHP extension integrated within ESRI ArcMap 10.2.2 (extAHP 2.0) (Table 5 and Table 6).

Table 5: AHP comparision matrix of the criteria.

	Slope	Aspect	Urban areas	Roads network	Radiation
Slope	1	1	3	3	0.143
Aspect	1	1	3	3	0.143
Urban areas	0.333	0.333	1	1	0.111
Roads network	0.333	0.333	1	1	0.111
Radiation	7	7	9	9	1

Comparision matrix of the criteria (Table 5) was filled in based on the scale values from Table 1. From the comparsision matrix we can see that solar radiation has a high importance (9 times) over proximity to urban areas and roads network and is also preferred strongly (7 times) over topography.

As the next step weights are generated (Table 6) based on previous pairwise comparisions. The higher the weight, the more important is the corresponding criterion.

Climatic conditions, i.e. solar radiation, are the most important criteria since they define the electricity production capacity and are therefore ranked the highest in the AHP criteria weigthing (Carrion et al.,2008a; Effat,2013; Georgiou and Skarlatos,2016; Tahri et al., 2015; Watson and Hudson, 2015). The second most important factors are aspect and slope, i.e. topography criteria (Carrion et al.,2008a; Effat,2013; Tahri et al., 2015). Aspect strongly influences the electricity production (Carrion et al.,2008a; Effat,2013; Georgiou and Skarlatos,2016; Sánchez-Lozano et al.,2013; Tahri et al.,2015; Watson and Hudson, 2015), whereas steep slopes are not considered suitable for solar park development (Brewer et al., 2015; Carrion et al.,2008a; Charabi and Gastli, 2011; Georgiou and Skarlatos,2016; Sánchez-Lozano et al.,2013; Tahri et al., 2015; Uyan, 2013; Watson and Hudson, 2015). Location criteria, i.e. accesibility factors, are of least importance (Carrion et al.,2008a; Effat,2013; Tahri et al., 2015).

Table 6: Criteria weights.

Factor	*Weight (%)*
Slope	13
Aspect	13
Distance from urban areas	5
Distance from roads network	5
Solar radiation	64
	100

To avoid any inconsistencies in pairwise comparisions, the Consistency Index (CI) is calculated. Perfectly consistent pairwise comparisions should obtain CI=0, but small values of inconsistencies are tolerable. Finally, Consistency Ratio (CR) is computed to determine the consistency. If CR < 0.10, the rankings are considered consistent. If CR ≥ 0.10, comparisions should be revised since they are not considered to be sufficiently consistent. CR = 0.026 was computed for AHP results, meaning pairwise comparision did not have to be recalculated.

Depending on the dataset the data have been classified into 2 or 4 suitability classes, keeping the number of land suitability classes to the minimum necessary. Land use, heritage and Natura 2000 data are classified into suitable and not suitable categories. All other data are classified into four suitability classes, reflecting the degrees of suitability.

4.4 Assignment of projected coordinate system

All the data were projected to Irish National Grid (TM65_Irish_Grid) (Table 7).

The Irish Grid is based on a modified Transverse Mercator Projection, using Airy Modified Ellipsoid as the figure for the earth. The Geodetic Datum is the 1965 Datum and the Vertical Datum is Malin Head (Ordnance Survey Ireland, 2016c).

Table 7: Parameters of the projected coordinate system TM65_Irish_Grid (ESRI ArcMap 10.2.2).

Projection	Transverse Mercator
False Easting	200000.0
False Northing	250000.0
Central Meridian	-8.0
Scale Factor	1.000035
Latitude Of Origin	53.5
Linear Unit	Meter (1.0)
Geographic Coordinate System	GCS_TM65
Angular Unit	Degree (0.0174532925199433)
Prime Meridian	Greenwich (0.0)
Datum	D_TM65
Spheroid	Airy_Modified
Semimajor Axis	6377340.189
Semiminor Axis	6356034.447938534
Inverse Flattening	299.3249646

4.5 Data preparation

4.5.1 Preparation of land use dataset

Land use is an important criterion included in PV siting analysis (Carrion et al.,2008a; Charabi and Gastli ,2011).

Irish agriculture is primarily grass-based (Tegasc,2016). Since 97.9% of county Kilkenny is covered under grassland (Figure 12), only land cover categories pastures and natural grasslands have been considered suitable in this study. All other land cover types were considered as a constraint.

According to the best practice guidelines arable land should be protected from any interference from non-agricultural uses (BRE National Solar Centre, 2013). Any unsuitable land cover categories such as woodland and any protected and ecologically sensitive habitats such as peatlands and heathlands have been excluded.

Consequently, both pastures and natural grasslands were classified as 1 and all other land cover categories classified as 0, indicating the presence of a constraint (Table 8, Figure 13).

Table 8: Classification of land use dataset.

Land use category	*Classification*
Continuous urban fabric	0
Discontinuous urban fabric	0
Industrial or commercial units	0
Road and rail networks	0
Mineral extraction sites	0
Green urban sites	0
Sport and leisure facilities	0
Non-irrigated arable land	0
Fruit trees and berry plantations	0
Pastures	1
Complex cultivation patterns	0
Land principally occupied by agriculture	0
Broad-leaved forest	0
Coniferous forest	0
Mixed forest	0
Natural grassland	1
Moors and heaths	0
Transitional woodland shrub	0
Inland marshes	0
Peat bogs	0
Salt marshes	0
Stream courses	0

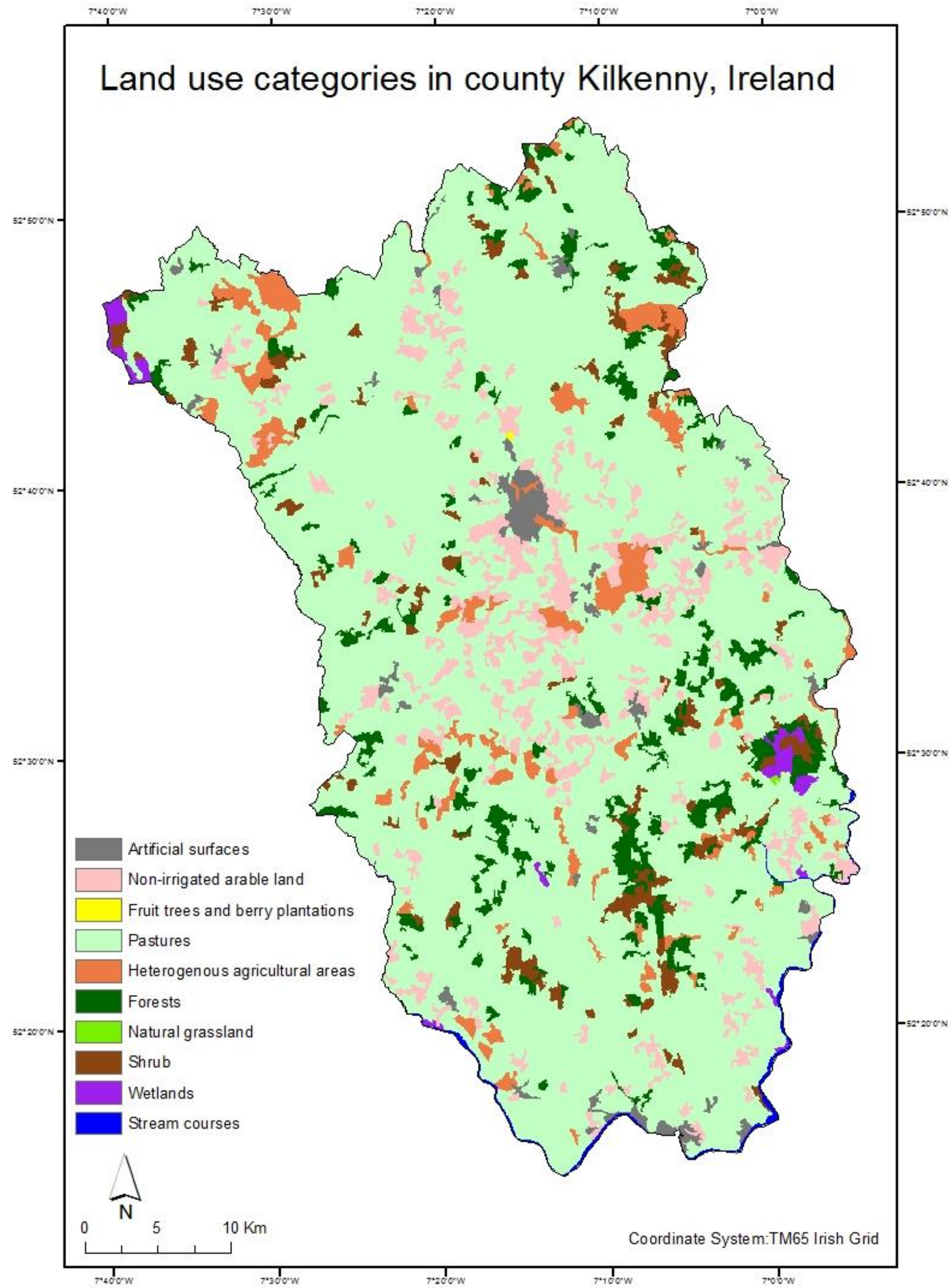

Figure 12: Land use categories of the study area.

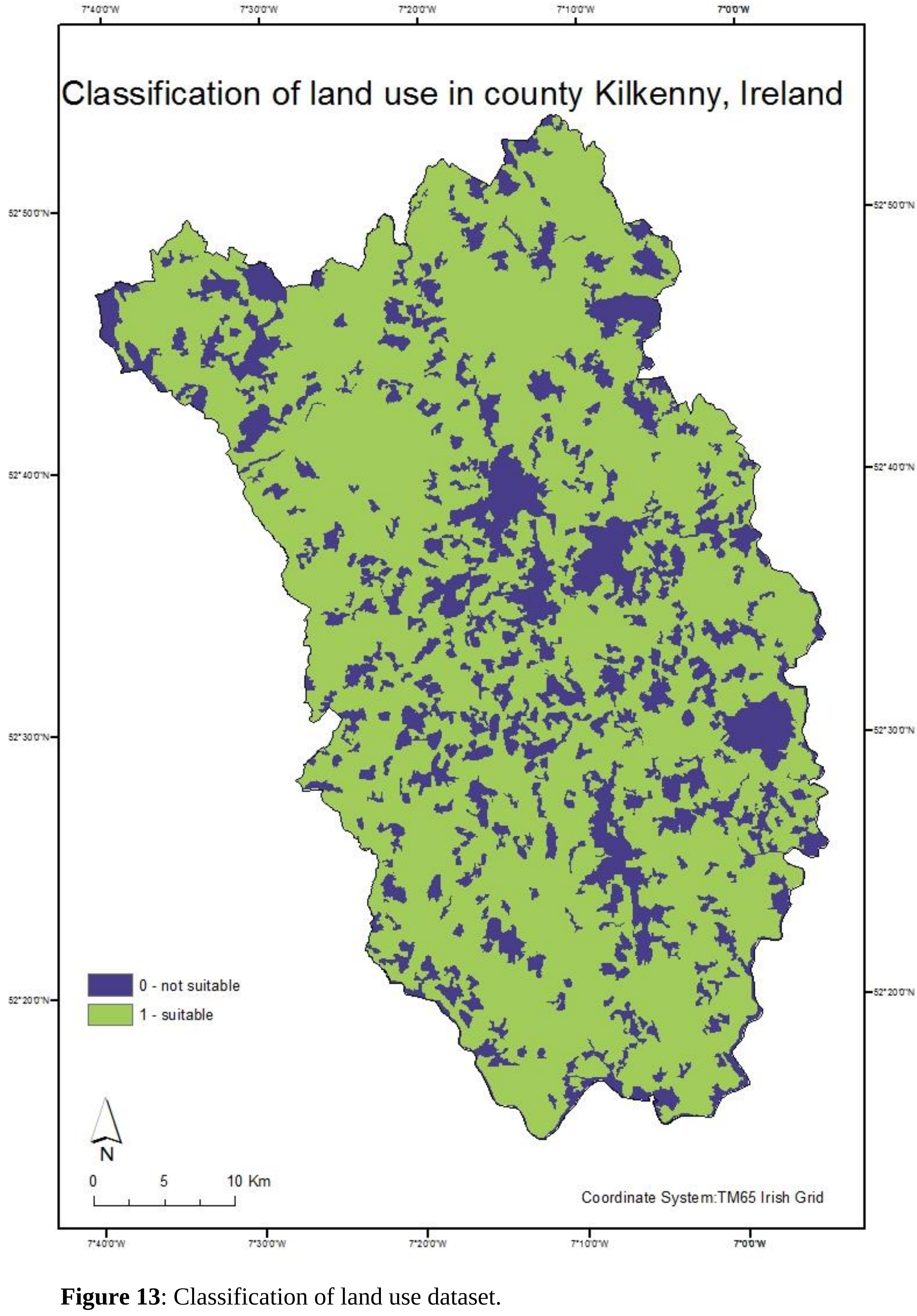

Figure 13: Classification of land use dataset.

4.5.2 Preparation of slope dataset

Slopes were calculated from the DEM with resolution of 90m (3 arc-seconds). Slopes can be expressed in percentages or in degrees. Percent of slope is calculated using the following formula (Eq.3, figure 14) (ESRI:ArcGIS Resource Center, 2014c):

$$\text{Percent of slope} = (\text{rise}/\text{run}) \times 100 \qquad \text{(Eq.3)}$$

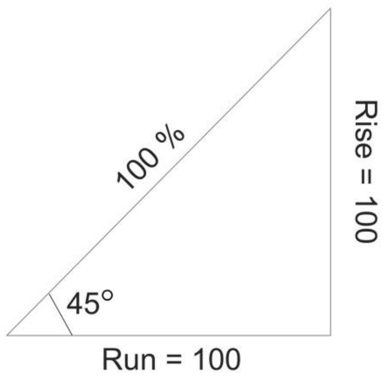

Figure 14: Calculating slope (after ESRI:ArcGIS Resource Center, 2014c).

The most suitable PV sites are located on the flat ground or on the mild slopes. The milder the slopes, the more important this type of area (Effat, 2013; Carrion et al.,2008a).

According to Uyan (2013) slope must be less than 3% for suitable solar farms sites. Similarly, Carrion et al. (2008a) found slopes less than 3% to be most optimal for grid-connected PV power plants. In a related study about electricity production capacity of PV power plants Carrion et al. (2008b) concluded that slopes greater than 2% can cause shadows cast by the panels themselves, resulting in the decrease of the plant´s performance.

Circa 68.9% of the study area has slopes less than or equal to 6%, therefore slopes up to 6% have been included in this analysis. To enable the most optimal plant´s performance, slopes up to 2% are scored the highest value 4. Slopes 2% – 4% are scored as 3, 4% – 6% scored as 2 and >6% scored as 1 (Table 9, Figure 15).

Table 9: Reclassification values for slope dataset.

Slope %	*Suitability*
0 - 2	4
2 - 4	3
4 - 6	2
> 6	1

Separately, slopes > 6% were considered as a constraint in creation of Boolean constraints dataset.

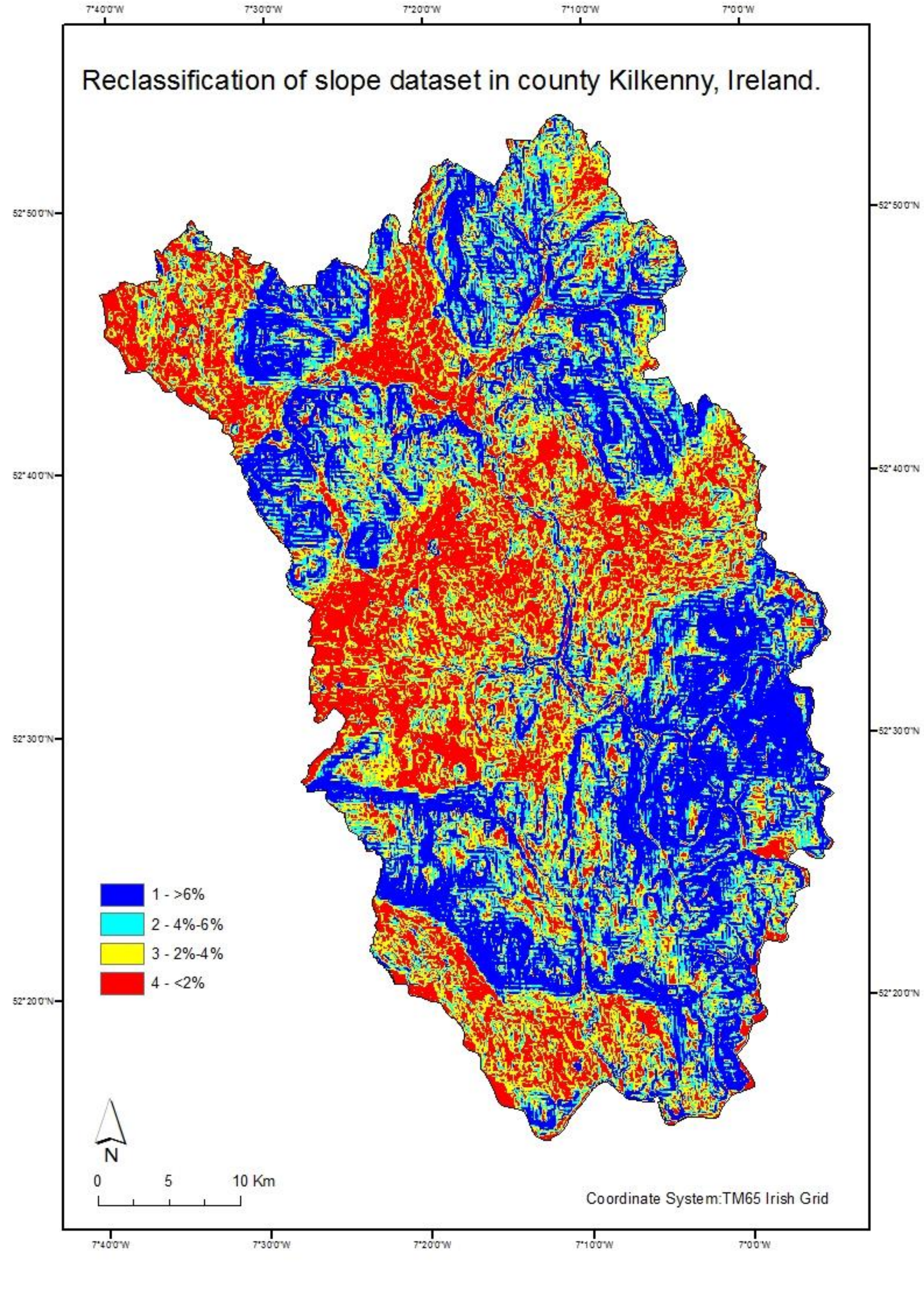

Figure 15: Reclassification of slope dataset.

4.5.3 Preparation of aspect dataset

Aspect was calculated from the DEM. Aspect identifies the slope direction and is measured clockwise from north in degrees from 0 to 359.9. Flat cells with zero slope are assigned an aspect of -1 (ESRI:ArcGIS Resource Center,2014a).

In the northern hemisphere the south-facing slopes receive the greatest amount of solar radiation. The southwest-facing slopes receive more sunlight in the afternoon than the southeast-facing slopes in the morning, resulting in higher radiation values and soil temperature (Chang, 1968).

Southeast to southwest directions are considered suitable in order to produce the most electricity (Effat,2013; Georgiou and Skarlatos,2016; Tahri et al., 2015; Watson and Hudson, 2015). South (157.5° - 202.5°) as the best direction in recieving solar radiation (Effat,2013; Tahri et al., 2015) is scored as 4, followed by southwest (202.5° - 247.5°) as the second best and southeast (112.5° - 157.5°) as the third best (Effat,2013; Tahri et al., 2015) ,scored as 3 and 2 respectively. Flat fields (-1°) are scored 4 similarly to the south aspect (Effat,2013) (Table 10, Figure 16).

Table 10: Reclassification values for aspect dataset.

Aspect (degrees)	*Suitability*
- 1 - - 0.000001	4
- 0.000001 – 22.5	1
22.5 – 67.5	1
67.5 – 112.5	1
112.5 – 157.5	2
157.5 – 202.5	4
202.5 – 247.5	3
247.5 – 292.5	1
292.5 – 337.5	1
337.5 - 360	1

Separately, all other directions except SE – SW and flat areas were considered as a constraint in creation of Boolean constraints dataset.

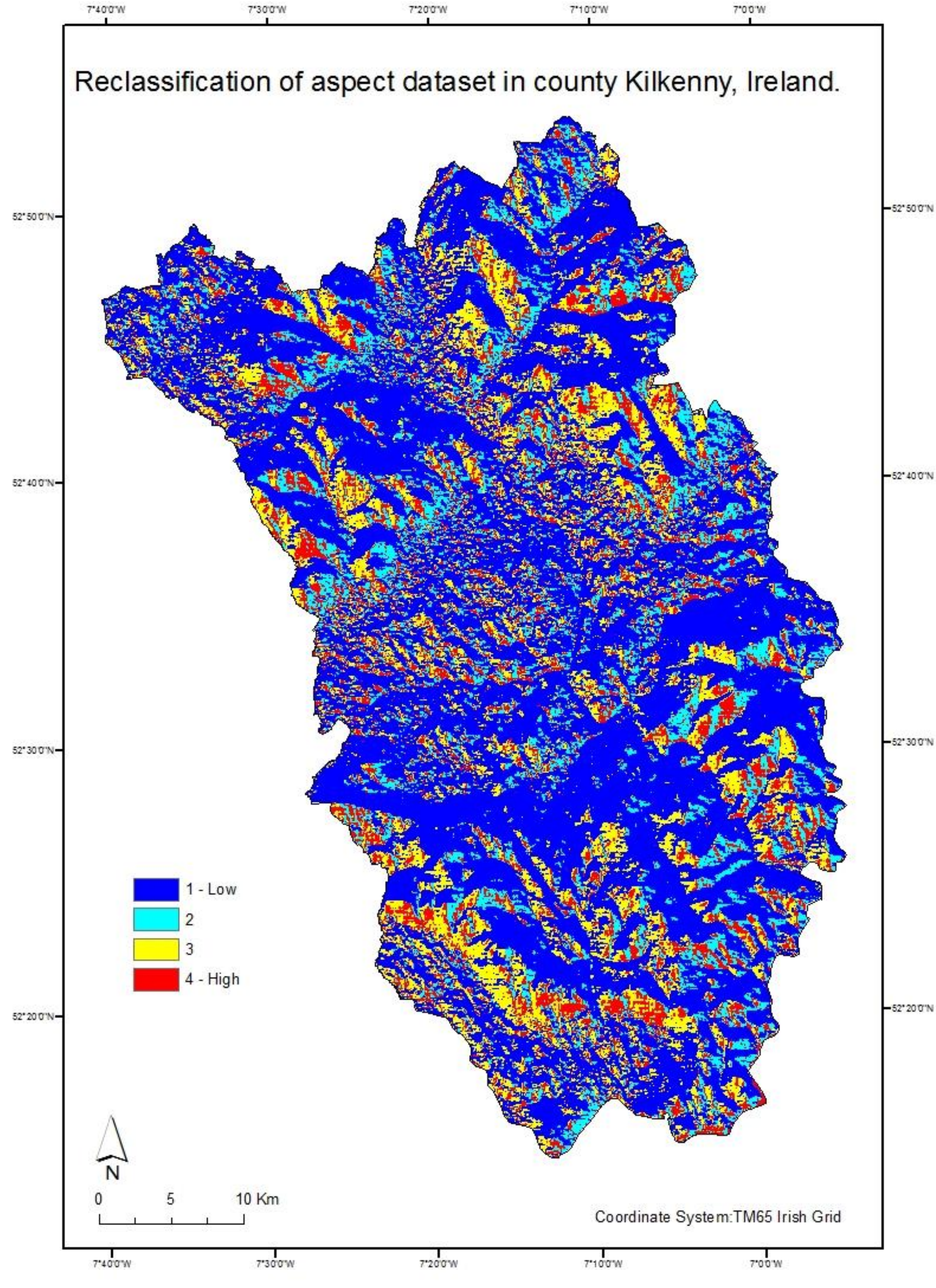

Figure 16: Reclassification of aspect dataset.

4.5.4 Preparation of solar radiation dataset

Area Solar Radiation tool (see chapter 2.4.3) was used to calculate diffuse, direct and global solar radiation for the study area. The solar radiation module estimates incoming radiation over time. A 90m x 90m DEM derived from SRTM was used as an input layer for the area. The time period used for the calculation: whole year with monthly interval for the year 2015. The output raster has units of watt hours per square meter (WH/m^2).

Global solar radiation layer was divided into four classes using Natural Breaks to classify (Table 11, Figure 17). Natural Breaks classification method was chosen because it is based on the patterns already inherent in the data, i.e. class boundaries are set where there are big jumps in the data values, grouping similar values and maximising the difference between the classes (ESRI:ArcGIS Resource Center,2014b).

Table 11: Reclassification values for solar radiation dataset.

Global radiation (WH/m2)	*Suitability*
468119- 830450	1
830450 - 876903	2
876903 - 907097	3
907097 - 1060391	4

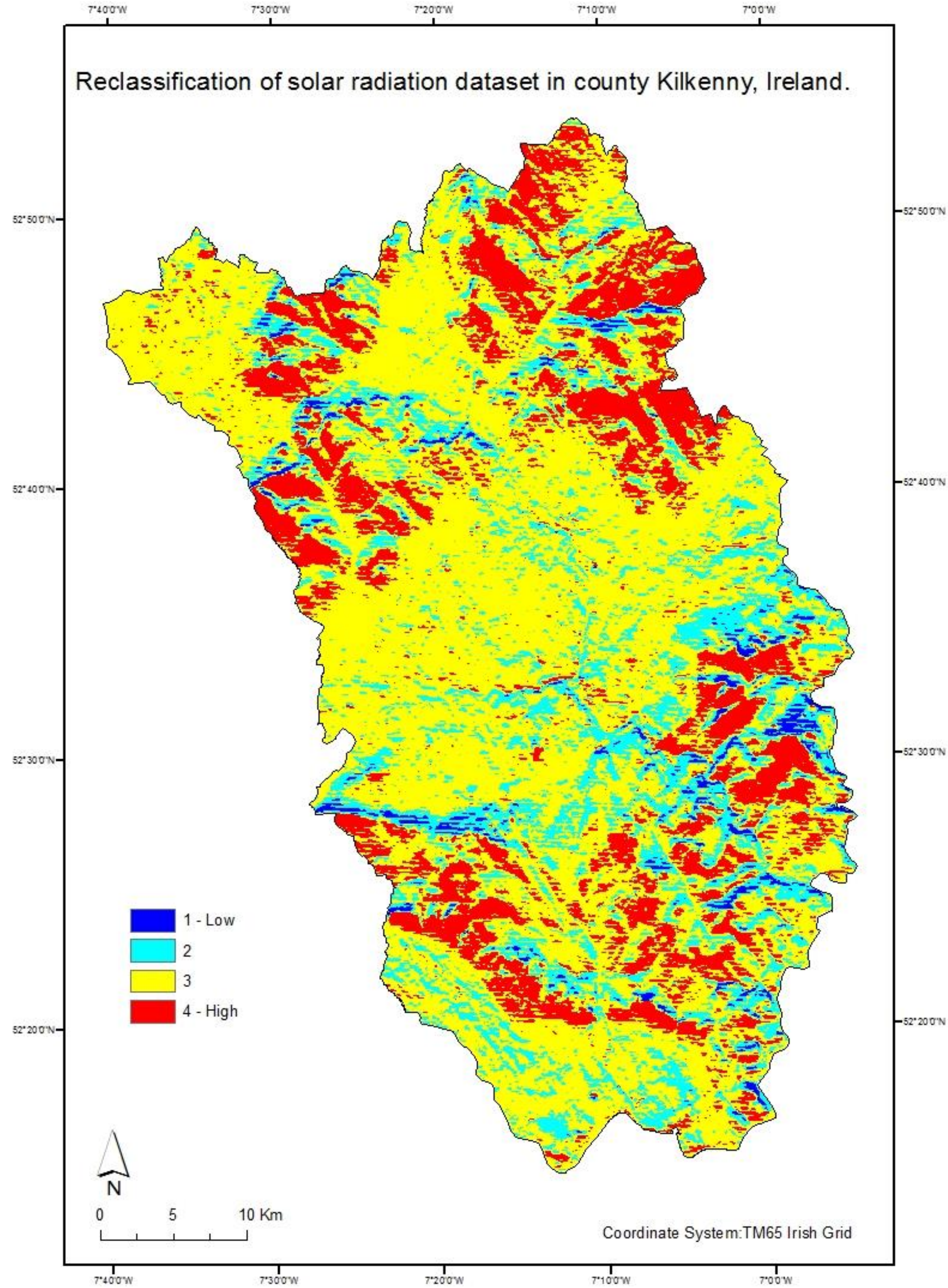

Figure 17: Reclassification of solar radiation dataset.

4.5.5 Preparation of distance from roads and railroads datasets

Proximity to roads and good site accessibility is a critical economic factor, influencing site contruction costs (Brewer et al.,2015; Uyan,2013; Watson and Hudson,2015). However, social risks such as theft and vandalism from the power plant facilities should be considered in close proximity of roads (Aragonés-Beltrán et al., 2010).

In solar farm siting studies constraints vary from 50 m buffer (Georgiou and Skarlatos,2016) to 200 m (Effat ,2013). A buffer of 100 m (Uyan,2013) as a mid-range value was considered suitable for this study and the distance >5000 m considered as least favourable (Uyan, 2013).

As proximity to all transport links is important, roads and railroads were treated the same way and the same prerequisites as for roads were applied to railroads (Watson and Hudson,2015). In order to be able to handle accessibility data more easily, one single roads network file was created by merging roads and railroads layers.

Straight-line distance from the roads network was calculated and four buffer zones created to be used as factor variable. Euclidian Distance is the most commonly used tool for the creation of suitability maps, when the distance to/from certain objects is needed and has been used in all GIS solar power planning studies mentioned in Table 2. The disadvantage of Euclidian Distance is the fact, that it may not always be possible to travel in a straight line but it may be necessary to go around certain obstacles (ESRI:ArcGIS Resource Center, 2014g).

Buffer zone < 100 m was scored as 4, buffer zone 100 – 2000 m was scored as 3, buffer zone 2000 – 5000 was scored as 2, buffer zone > 5000 m was scored as 1 (Table 12, Figure 18).

Table 12: Reclassification values for roads dataset.

Roads network	*Suitability*
0 - 100	4
100 - 2000	3
2000 - 5000	2
> 5000	1

Separatley, a buffer of 100 m was applied to roads and considered as a constraint.

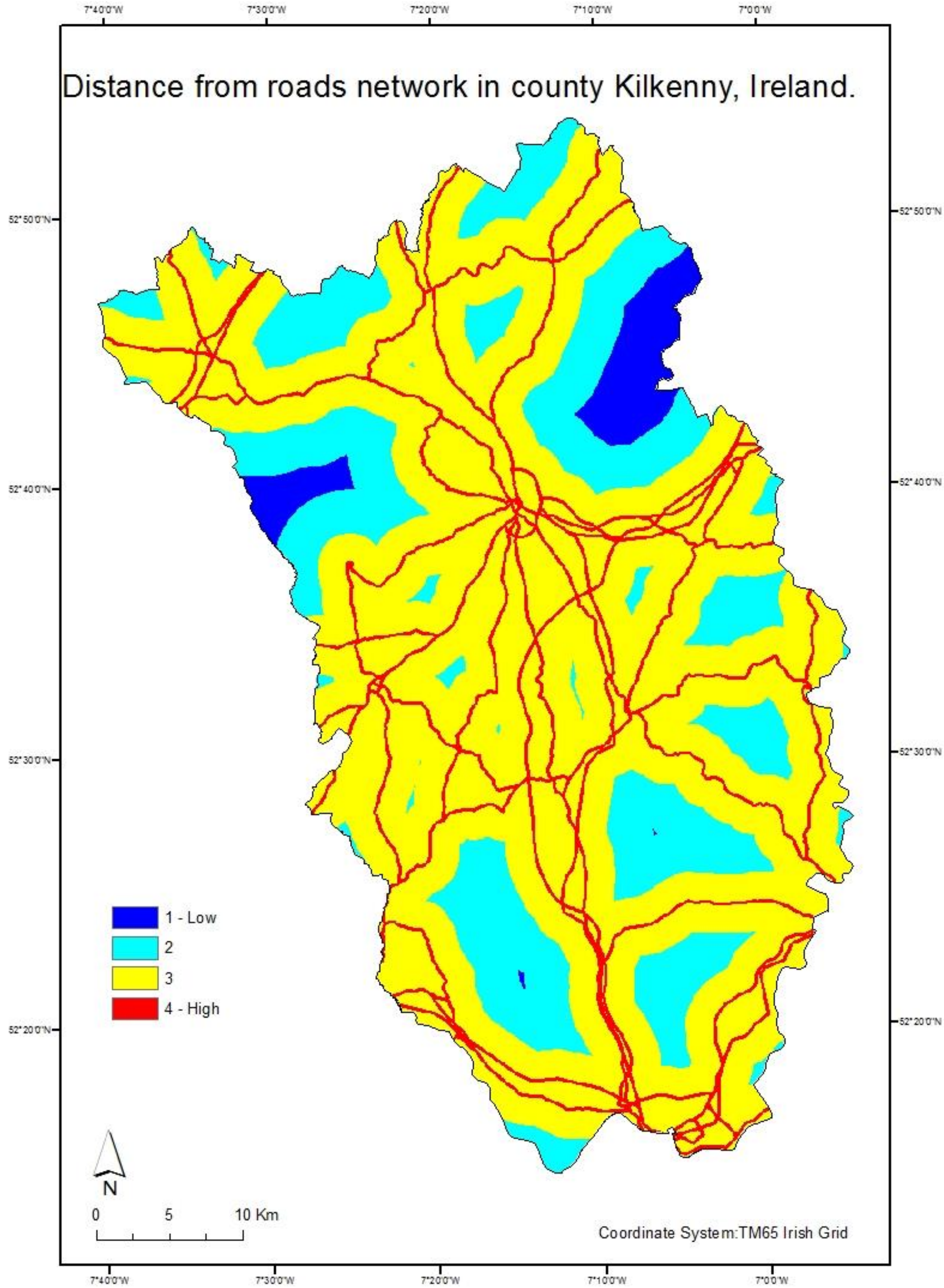

Figure 18: Reclassification of roads network dataset.

4.5.6 Preparation of distance from urban areas dataset

Areas < 0.4 km^2 or with population >100 but < 5000 inhabitants are classified as urban areas in the Ordnance Survey Ireland dataset used in this study. Those built-up areas, which have less than 100 inhabitants but are main villages or cities of the regional/local administrative units, are also included.

Proximity to populated areas is an important economic factor in evaluating site suitability (Effat,2013; Tahri et al. 2015). At the same time, solar farms can have a significant visual impact (Watson and Hudson,2015) and cause negative impacts on the urban area growth and population (Uyan, 2013). Both Watson and Hudson (2015) and Uyan (2013) considered a 500 m buffer zone around residential areas appropriate.

Buffer zone < 500 m was scored as 4, buffer zone 500 – 5000 m was scored as 3, buffer zone 5000 – 10 000 m was scored as 2, buffer zone > 10 000 m was scored as 1 (Table 13, Figure 19).

Table 13: Reclassification values for urban areas dataset.

Urban areas	*Suitability*
0 - 500	4
500 - 5000	3
5000 – 10 000	2
> 10 000	1

Separatley, a buffer of 500m was applied to built-up areas and considered as a constraint.

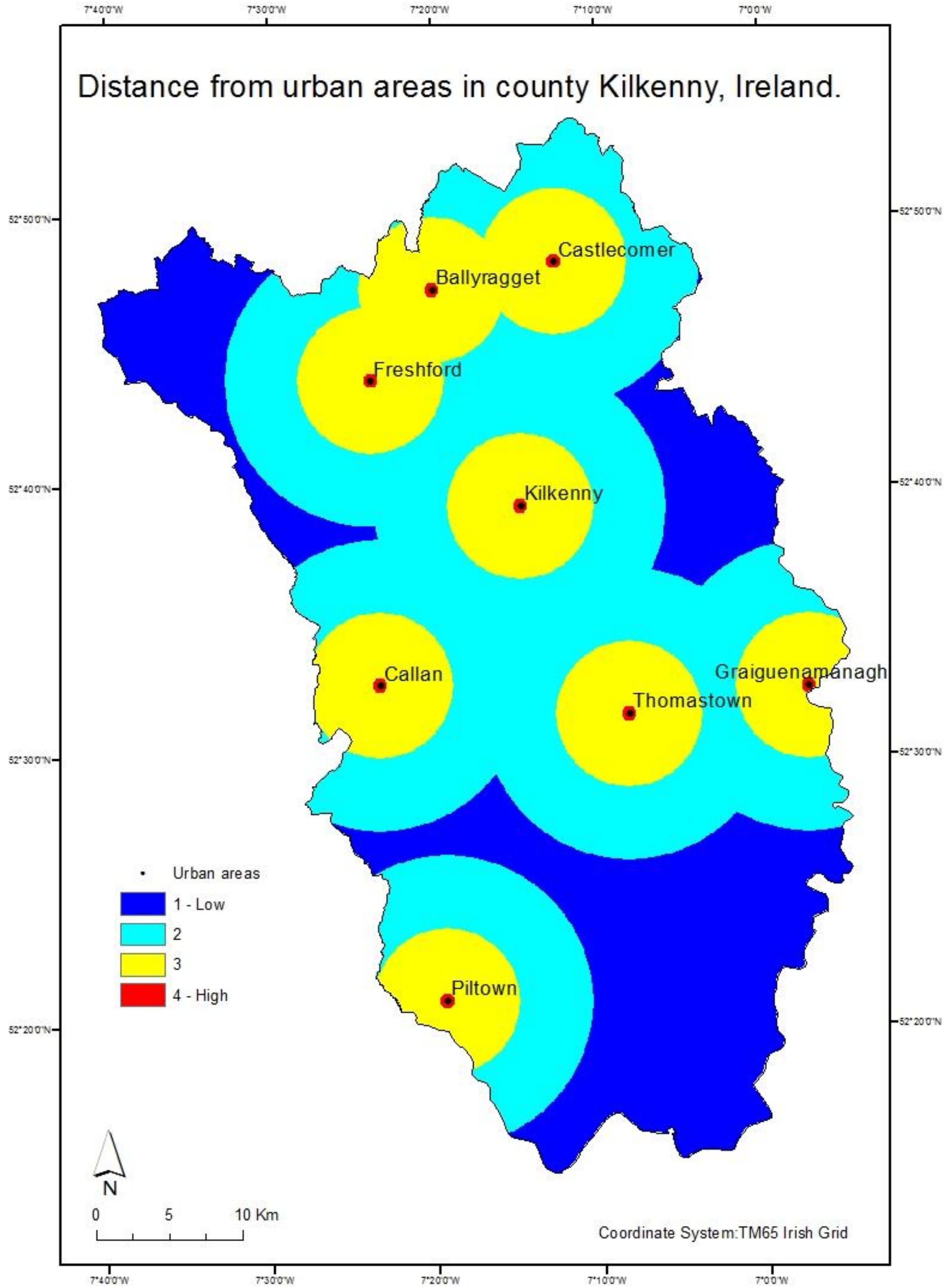

Figure 19: Reclassification of distance from urban areas dataset.

4.5.7 Preparation of distance from heritage dataset

Historic buildings, monuments and sites need to be protected and preserved. Heritage protection is an integral part of any planning system and a development on these sites could damage the cultural heritage of the area (Watson and Hudson,2015). Since no guidelines exist for solar developments in Ireland, UK-specific buffer distances from Watson and Hudson (2015) have been applied in this study.A buffer zone of 1000 m was created around the heritage objects and considered as a constraint (Figure 20).

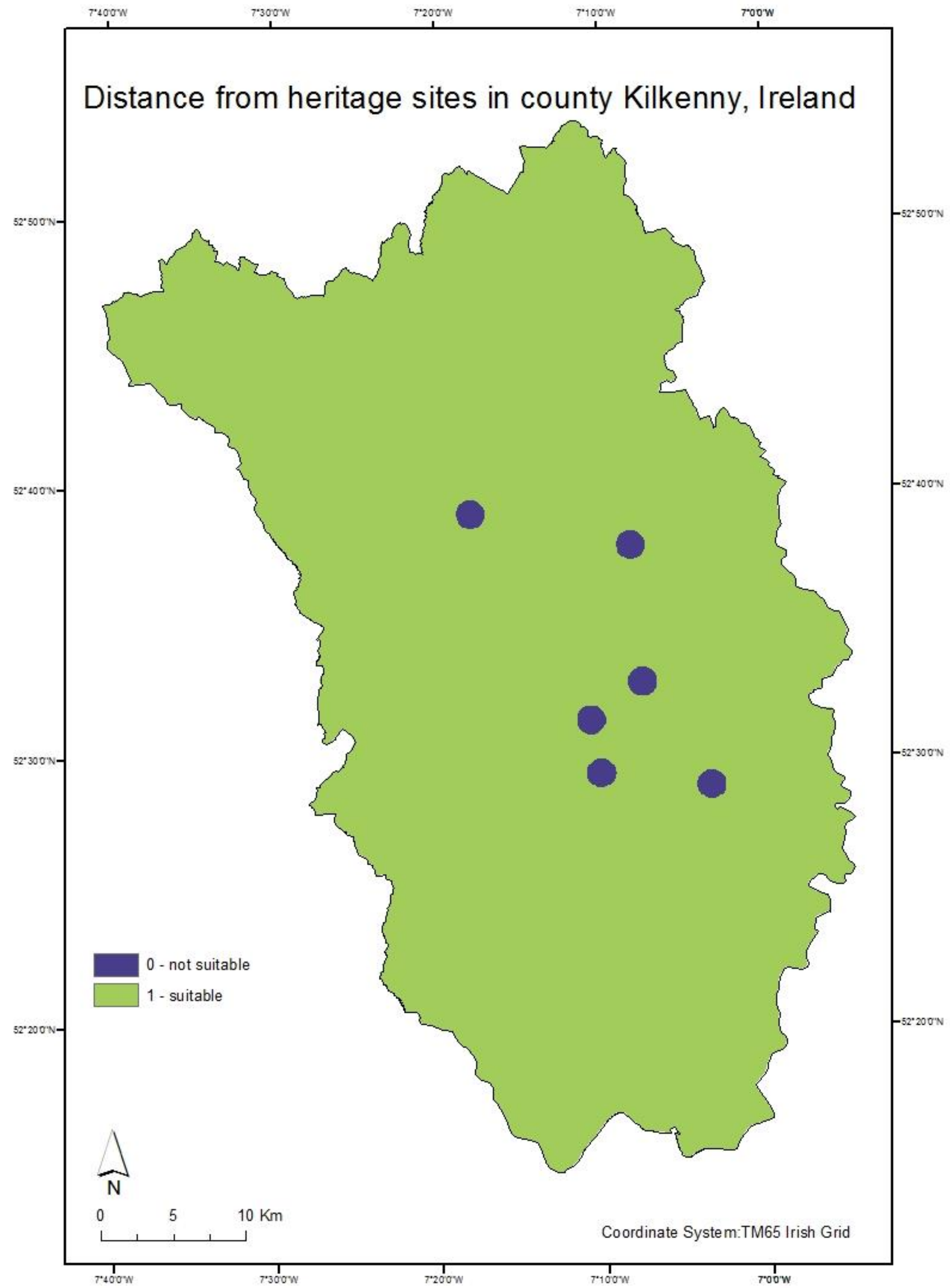

Figure 20: Buffer zones around heritage sites.

4.5.8 Preparation of distance from Natura 2000 dataset

Natura 2000 protection areas are internationally recognised high ecological importance sites. A buffer zone of 1000 m was created around the protection areas and considered as a constraint (Watson and Hudson,2015) (Figure 21).

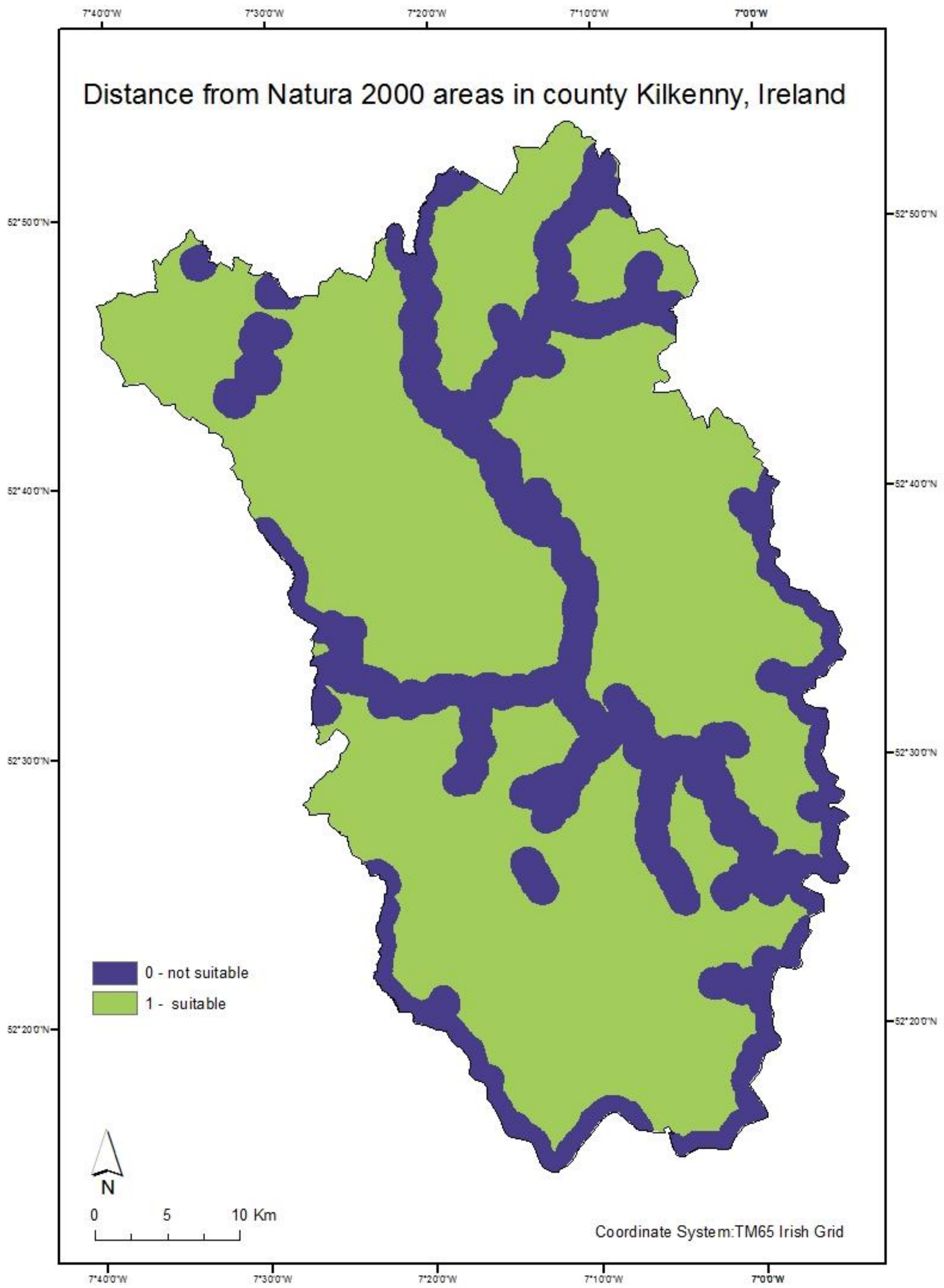

Figure 21: Buffer zones around Natura 2000 protection areas.

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5. Results

5.1 Overlay Analysis

5.1.1 Weighted overlay of factors and Boolean overlay of constraints

Weighted Overlay tool was used to complete the suitability modeling. Slope, aspect, insolation, distance from urban areas and distance from roads network were used as input layers. The input criteria were reclassified into a common preference scale as indicated in tables 9 – 13. The more favourable the criteria range, the higher the value. The criteria were weighted according to their importance as per AHP results (Table 6, Figure 22).

All constraints layers were reclassified using binary scale, where 0 represented the presence of a constraint and 1 represented the absence of a constraint. The constraints layers (land use, slope, aspect, distance from urban areas, distance from roads network, distance from heritage, distance from Natura 2000 sites) multiplied together produced the final constraints layer (Figure 23).

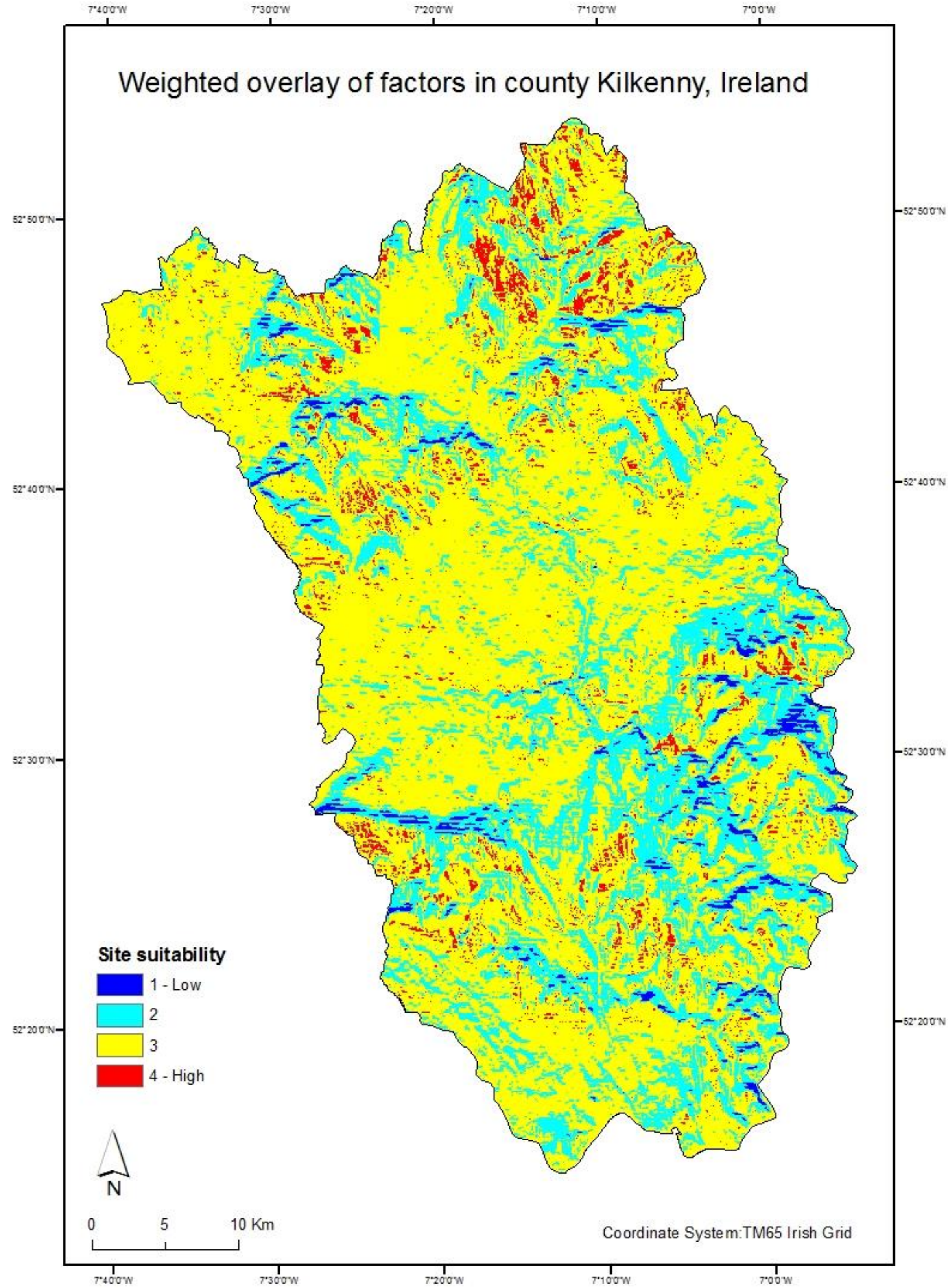

Figure 22: Weighted overlay of factors.

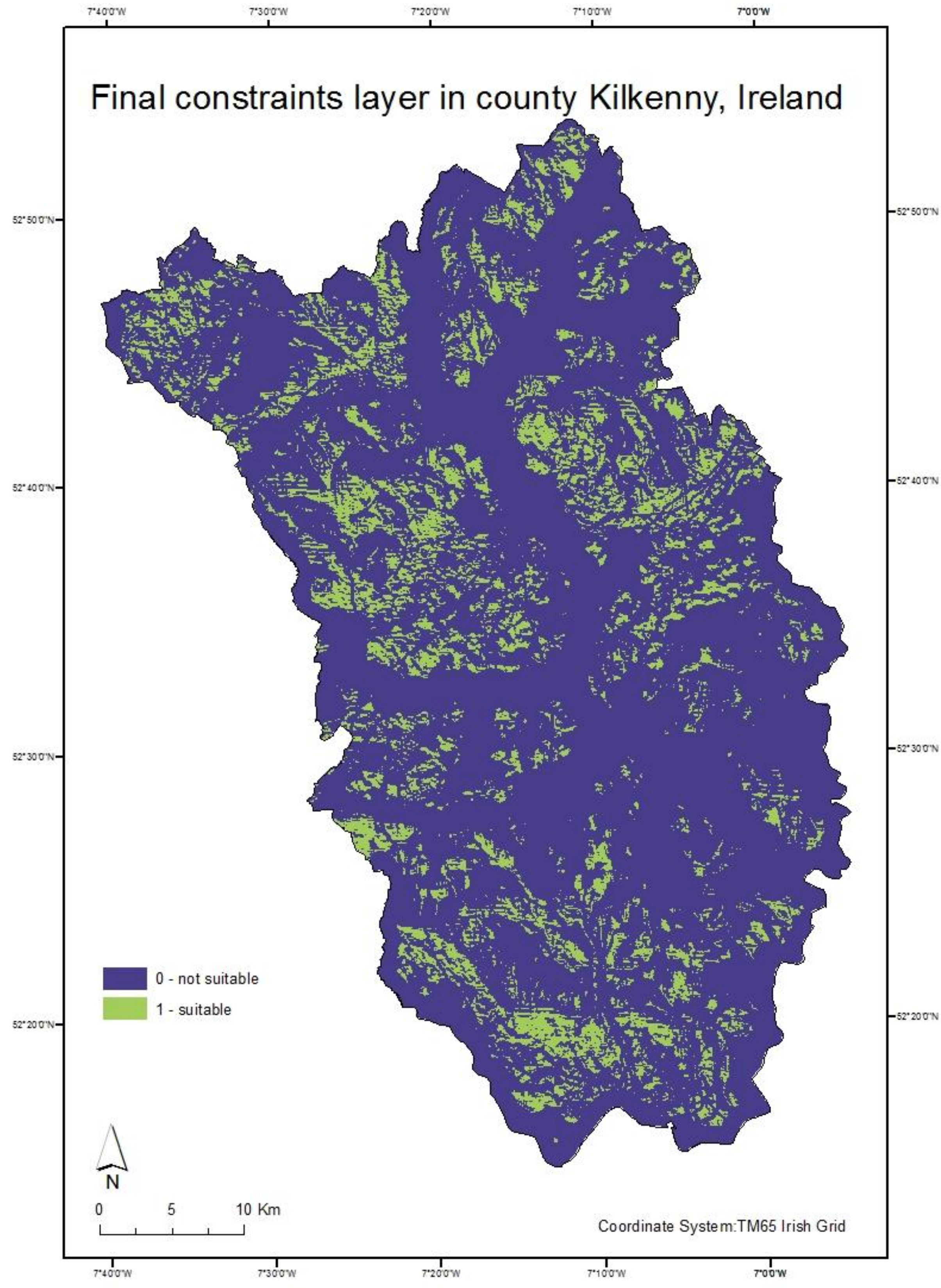

Figure 23: Final constraints layer.

5.1.2 Final suitability map

The weighted factors layer and constraints layer multiplied together produced the final suitability map (Figure 24).

Final suitability map consists of three suitability values 0, 1 and 2. The value of 0 represents constraints, i.e. non-suitable areas. The maximum suitability value of 2 that can be reached, would be the best possible locations for a solar farm and therefore considered as „most suitable“. The suitability value of 1 is considered as „moderately suitable“.

In addition to the highest suitability value, the selection criteria for potential sites includes the site area criteria. According to National Renewable Energy Laboratory of U.S. Department of Energy (2012) utility-scale solar plants project size starts from 5 MW. A similar approach has been adopted in the United Kingdom, where 5 MW marks the line between small-scale and large-scale solar farms. Projects below 5 MW are eligible for Feed-in Tariff (FiTs), whereas projects above 5 MW qualify for Contracts for Difference (CfDs) (DECC,2014).

A 5 MW installation is estimated to require circa 25 acres (i.e. 10.12 ha) of land and to produce enough energy to power 1515 homes a year on average (Solar Trade Association, 2016).

5042.3 ha (2.43%) was found to be „most suitable“ and 25 821.7 ha (12.46%) to be „moderately suitable“ for ground-mounted PV solar plants. 85.11% of the study area is not suitable for solar farms. The majority of the most suitable sites are located in the northeast of the county, followed by northwest and the southern areas.

In comparision to the „most suitable“ class, the lower suitability values usually scored more poorly in solar radiation category. Class 2 areas scored relatively high in all the factor categories, resulting in higher values from solar radiation usually ovelapping with higher values from other categories.

1384.9 ha (0.67%) consisting of 72 largest sites from the „most suitable“ category also fulfill the minimum size criteria area of over 10 ha for utility-scale solar PV and are chosen as potential sites for solar farm development in this study (Figure 25).

While this is highly unlikely that solar plants would be set up at all 72 locations, renewable energy usage in Republic of Ireland would in this case increase by 24.85%. Just one 5MW solar plant would increase the total renewable energy usage by 0.18% and the currently installed solar PV by 2.5 times.

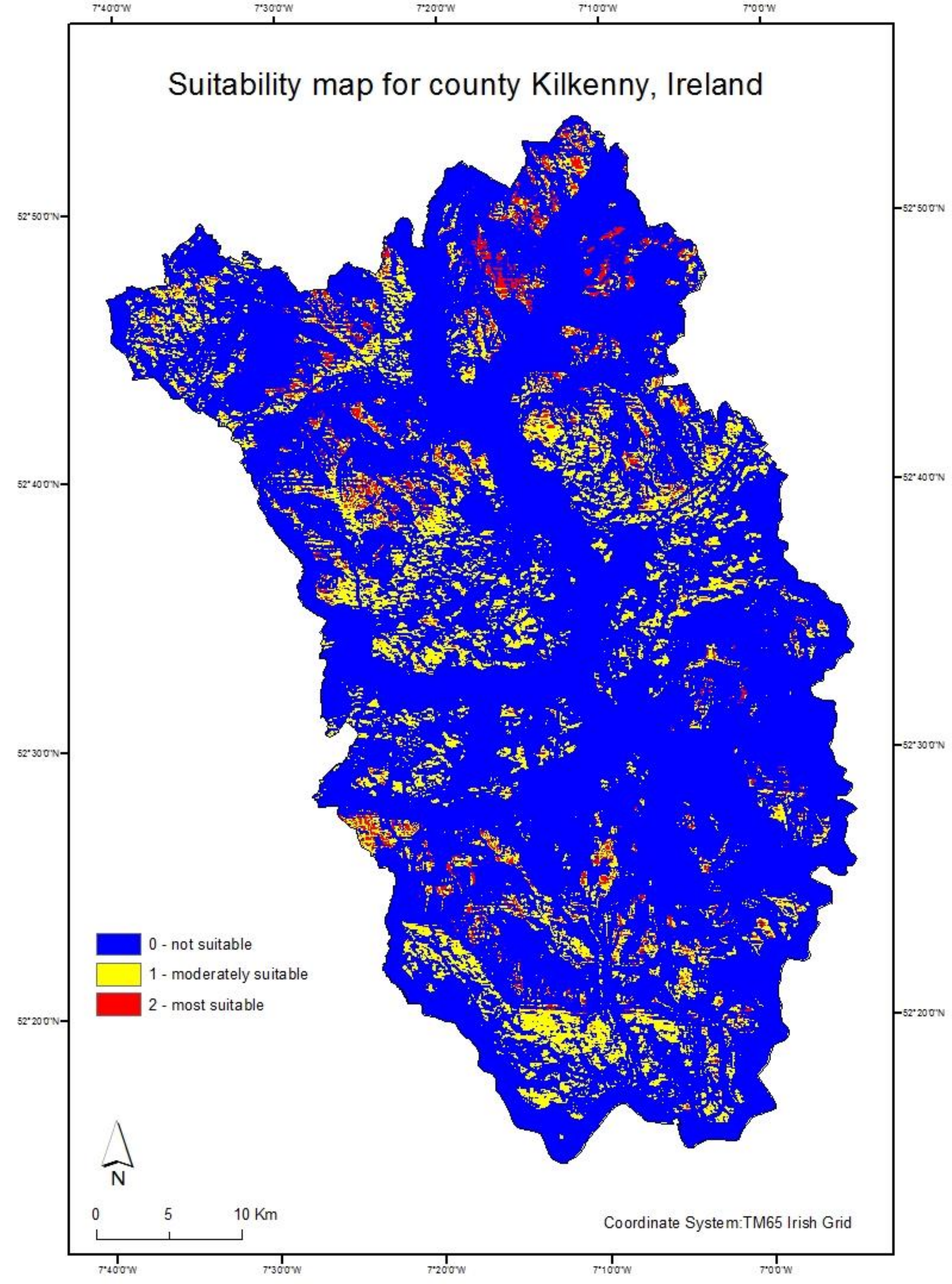

Figure 24: Final suitability map.

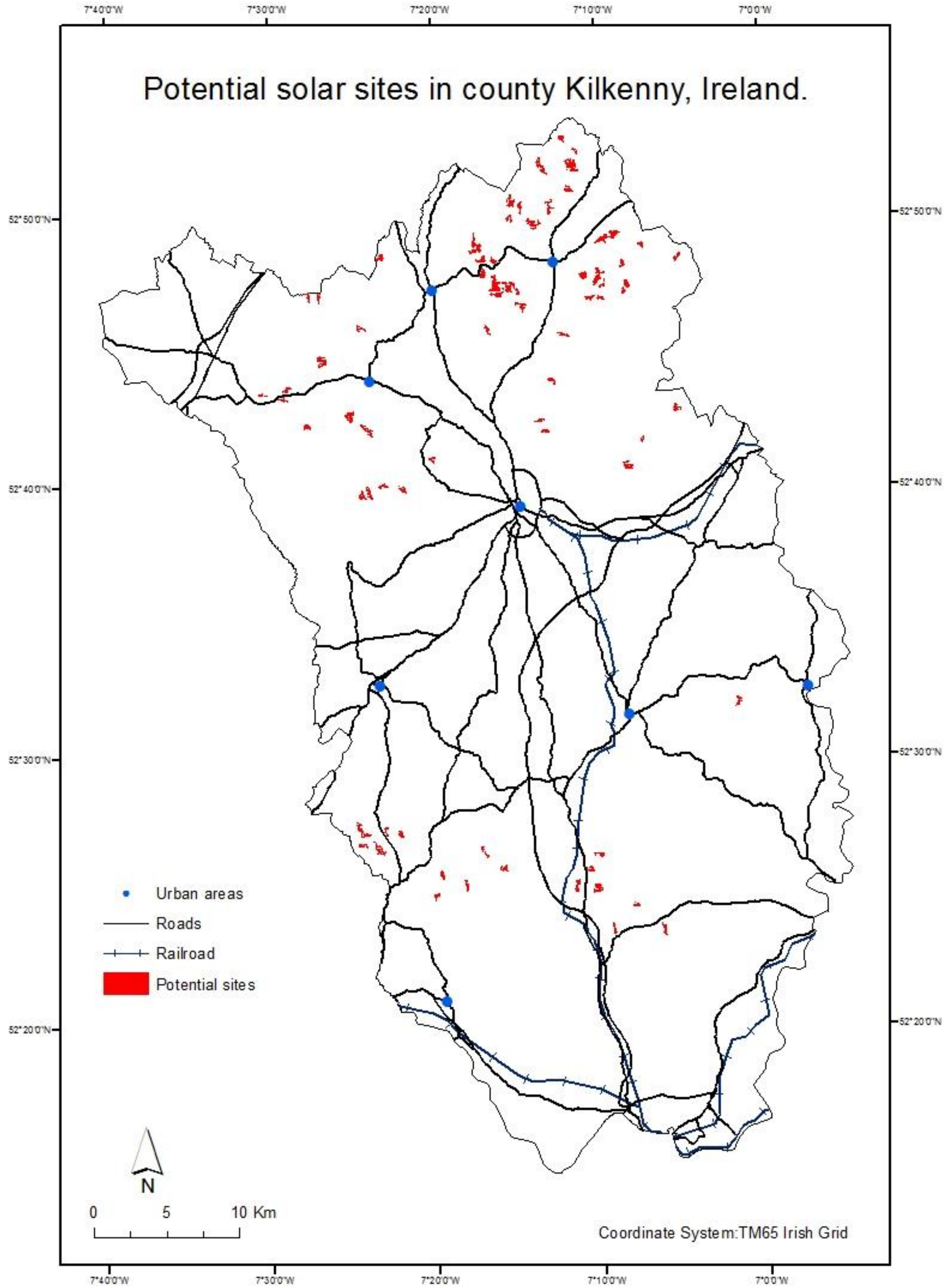

Figure 25: Potential solar sites.

5.2 Sensitivity analysis

Due to subjectivity and uncertanity of the values the decision models are based on, sensitivity analysis should be performed to check how alterations in parameters change the results (Meszaros and Rapcsak, 1996). Input data are slightly modified and different scenarios can be generated, in order to be able to compare them to the suitability map produced earlier (Ishizaka and Labib, 2011).

First, equal weightings for all factors (five weights of 20% each) (Figure 26) were used to check the stability of the model (Nekhay et al., 2009). Secondly, the model was tested without the influence of the climatic factor (Figure 27). Solar radiation which has the greatest weight of all the factors was omitted, whereby the remaining variables kept the same proportions to each other as produced in AHP criteria weighting (slope and aspect factors remained with weights of 35% , urban areas and roads network factors with weights of 15%).This scenario evaluates the suitable locations without considering the climatic factor influencing solar farm´s performance.

According to the equal weights sensitivity analysis, the stability of the model can be concluded, since the main trends observed by visual inspection match the original model.Although considerably less class 4 values emerged, these are still present in the same preferred region. In either case, the highest suitability values are mostly scattered in the northeast of the study area.

Scenario two did not consider solar radiation data. As a result, the suitable areas do not follow the same patterns as in the original model.Higher values are predominantly determined by the slope factor.

Both sensitivity analyses results show less highest suitability values (Figure 28). The „most suitable" category decreased to 0.0085% and 1.07% respectively, compared with the 2.43% found in the suitability analysis. The „moderately suitable" category increased in the first scenario from 12.46% to 12.66% and decreased to 10.44% in the second scenario. Additionally, the „least suitable" category values that were missing in the suitabilty analysis were presented with 2.23% and 3.38% shares. No potential sites were identified in sensitivity analyses, as none of the highest category sites met the minimum size criteria.

Overall, in both cases a shift towards the lower suitability categories can be identified, i.e. highest category values cover a lesser area. The outcome visualises the sensibility of the suitability layer to the influences of criteria weights and is found to be both, sensitive and robust enough to incorporate different factors originating from possible various interest groups (Feick and Hall, 2004).

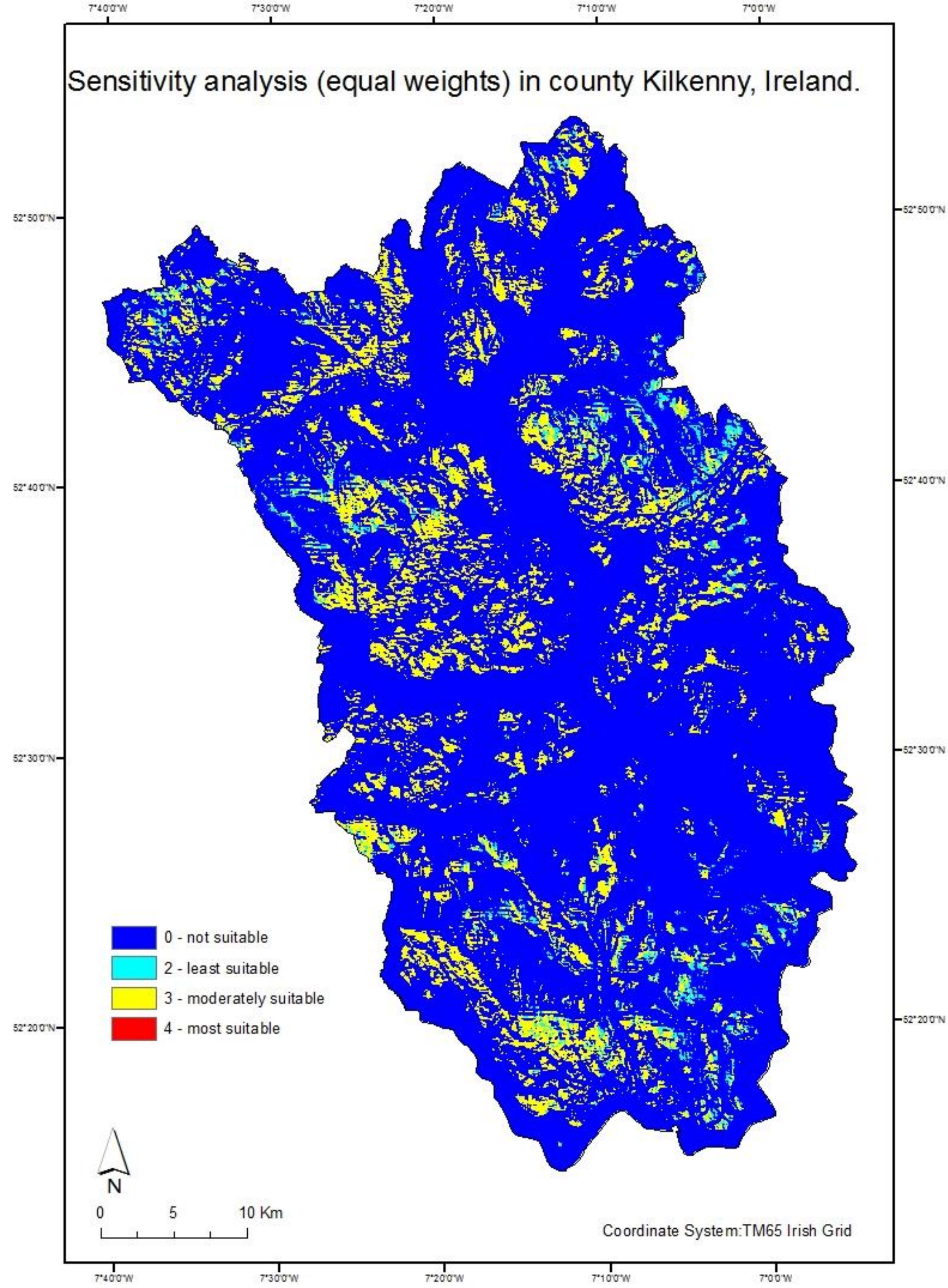

Figure 26: Sensitivity analysis with equal weights.

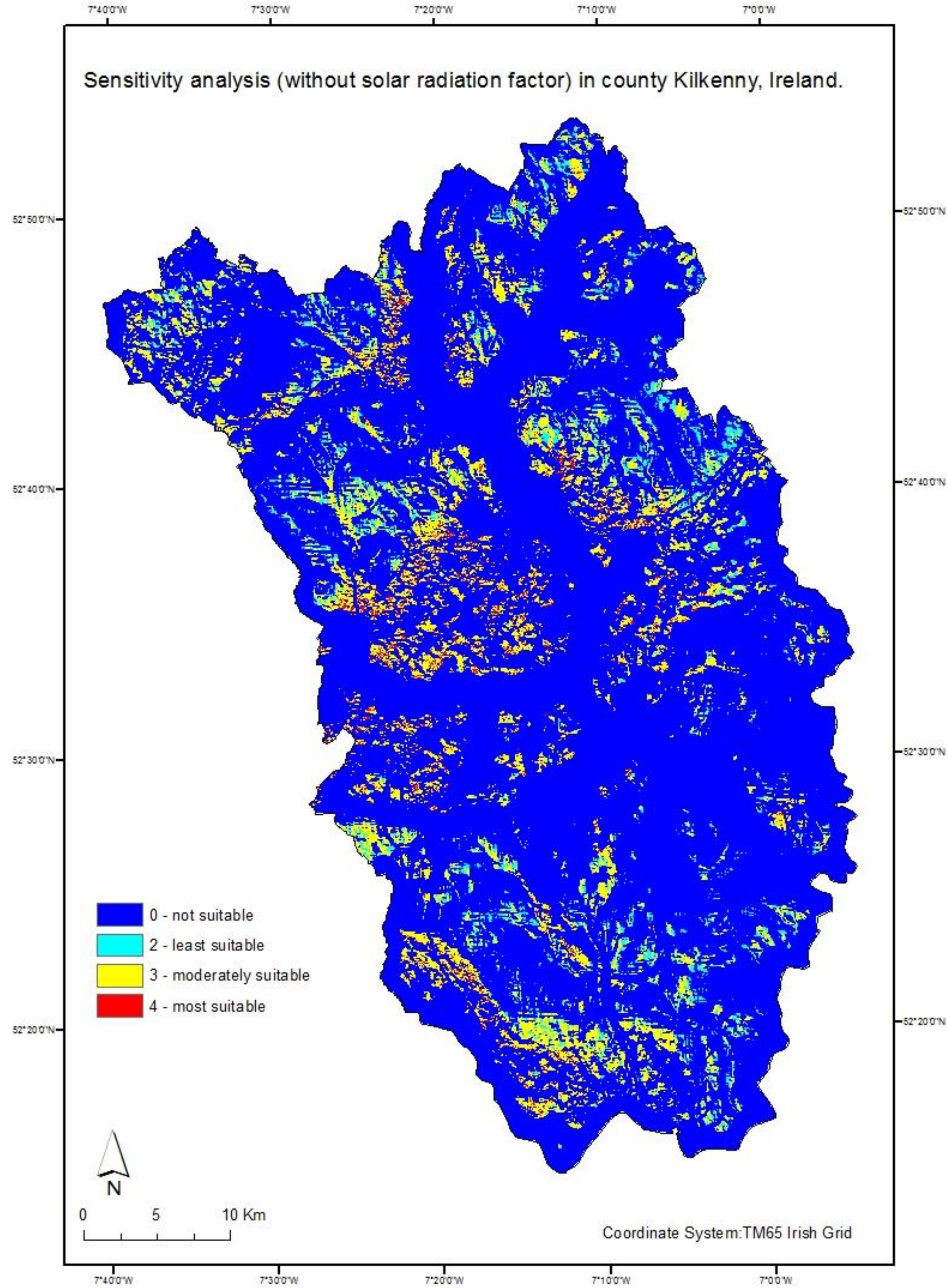

Figure 27: Sensitivity analysis without solar radiation factor.

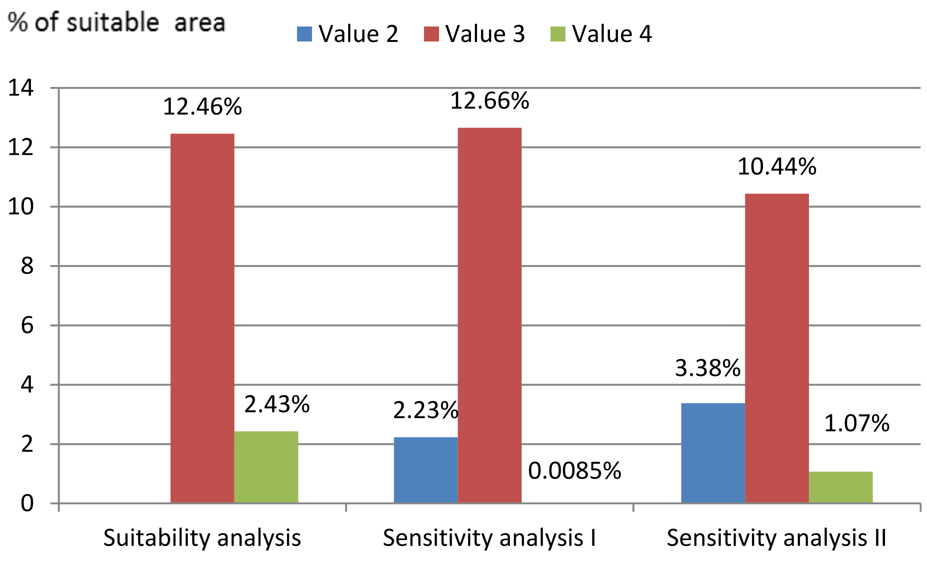

Figure 28: Comparision of suitability and sensitivity analysis results.

6. Discussion

Solar PV has become a big challenger to conventional electricity generation technologies and has shown the ability to adapt all over the world (Solar Power Europe, 2015). Large PV developers in particular can be seen as the electricity producers of the future (IEA, 2015). Although regions with lower irradiation values in Northwest Europe have less favourable conditions for solar electricity generation, the example of Germany and United Kingdom demonstrates that solar PV can be succesfully deployed (Šúri et al.,2007).

The results of this study are promising and show multiple potential sites. Most of the highest score values are located in the northeastern part of the study area. High suitability is observed to be associated with higher solar radiation values. High insolation values in turn are found to be dependent on slope and aspect. Topographic factors slope and aspect may vary already within short distances, influencing incoming solar radiation. Higher elevation values and southern directions of the slope mean higher levels of solar radiation.

No higher scores were found in the middle of the study area. Upon closer examination of this area it becomes apparent that solar radiation values in general are lower in this region.

As previously mentioned, the solar radiation calculation tool in ArcGIS calculates the insolation maps based on DEM and already accounts for topographic features. Therefore it could be argued that slope and aspect may not be critical to consider. However, considering the importance of topography, both aspect and slope have been included in most solar power planning studies (Carrion et al.,2008a; Georgiou and Skarlatos,2016;Sánchez-Lozano et al.2013;Tahri et al.,2015; Watson and Hudson, 2015) and here. Nevertheless, Triantaphyllou and Mann (1995) suggest the decision maker to stay cautious when some alternatives in AHP appear to be very close with each other.

On the contrary to slope and aspect, altitude as an possible factor influencing solar irradiance (Fu and Rich,1999) but also as a technical criteria increasing the investment costs (Georgiou and Skarlatos,2016) does not have a high enough importance to be considered separately (Watson and Hudson, 2015). Due to the very mountainous terrain of the study area in Cyprus only Georgiou and Skarlatos (2016) have included altitude in the site selection analysis.

It must be noted that though no transmission lines data was used in this study, the majority of the potential sites selected based on other environmental and economic factors, are located within a short distance from a major road and just a few kilometres from the nearest town. The close proximity of infrastructure lets to assume that connection to the national grid should be no problem. Although an off-grid PV system also remains an alternative option, these are traditionally only used in very remote areas (e.g. for mines in Australian desert regions) or in developing countries with no access to the grid.

DEM with resolution of 90m was used in this study as an input for slope, aspect and solar radiation calculations. In several GIS solar power planning studies (Table 2) DEM resolution has not been mentioned. However, Watson and Hudson (2015) used DEM with resolution of

90 m in England, hence the results of this study are one-to-one comparable to the findings in their research.

The possible influence of the spatial resolution must be kept in mind. The accuracy of DEM is represented by it´s spatial resolution (Takagi,M, 1998). The lower the DEM resolution, the lower the accuracy of slope and aspect data (Chang, K. and Tsai,B., 1991). Using coarser resolution DEM can lead to the underestimation of the slopes (Wainwright et al.,1999). Chang and Tsai (1991) showed that as the DEM resolution decreases slope differences concentrate in areas of steep slopes. Since the landscape of the study area is moderately hilly, it can be concluded that the topography generally corresponds to the resolution of 90m. Also, a random noise and striping error exists in SRTM DEM that affects slope and aspect and can cause errors especially in flat areas (Perego, 2009).

In terms of methodology, this study demonstrated the importance of including and analysing multiple choice alternatives by using the appropriate MCDM method. The chosen AHP methodology allows to include expert knowledge logically into analysis and it´s hierarchical structure is easy to understand. Literature reviews confirmed this choice of methodology in solar energy site assessment analysis (Carrion et al.,2008a; Effat,2013; Georgiou and Skarlatos, 2016; Sánchez-Lozano et al.,2013; Tahri et al.,2015; Uyan, 2013; Watson and Hudson, 2015). At the same time it must be kept in mind that results could have been different using a different method.

In the absence of country-specific guidance for the development of solar farms, the criteria used in this study and the choice of weights are based on the subject-related studies from other countries. Although some of the countries lie in other climate zones with different environmental aspects, meaning different factors could potentially play a more or less significant role in other regions, there is generally an agreement on the importance of different criteria. Yet once the relevant legislation is introduced, it might alter the criteria adopted for this study.

The study results are found to be similar to other researches in the field. In Ireland, 85.11% of the study area accounts for constraints and cannot be considered for a PV siting whereby the „most suitable“ area accounts for 2.43% .

In a related study, Watson and Hudson (2015) used MCDM and AHP approach in their GIS analysis to identify solar farm developments in central Southern England. The key difference between the two studies was that Watson and Hudson (2015) were able to include the main electricity cables data in their analysis while this study was unable to do so. The "most suitable" area accounted for 2.02% from the study area and a constraint layer of 81.4% was produced. In both studies, parcels were found to be most limited by solar radiation and additionally by distance to network connection in England.

The study conducted by Sánchez-Lozano et al. (2013) assessed optimal placement of PV solar plants in south-eastern Spain using AHP and TOPSIS method. The study considered a total of 10 factors, while 5 factors were included in this analysis. Average temperature factor used in their analysis would not be relevant to be considered in this case study, because too hot temperature (that would rarely occur in Ireland) decreases solar cells performance (Dubey et al., 2013). 86.15% of the study area was found being covered by constraints and "most suitable" area corresponded to 3.206% in Spain. Due to very good climatic conditions in the region location criteria was weighted higher than climate criteria. Consequently, land suitability in Spain was mostly limited by the lack of human infrastucture and rarely by solar irradiation.

The outcome of the sensitivity analysis showed stability of the suitability model. Both tested scenarios resulted in considerable decrease of the most suitable category, whereby the moderately suitable category emerged as more stable. The most suitable category was found to be more sensitive, which can be explained by exclusion or decrease of the solar radiation proportion.

6.1 Limitations of the study

Multi-criteria analysis refers to assessing multiple, possibly conflicting, criteria choices.The method depends on the views of decision makers, based on the information available at a given time. Therefore, the results may or may not present the ultimate truth.

Availabilty of other datasets could contribute to improvement of the study. Due to unavailability of transmission lines data, this criterion was not considered in the current analysis. Additionally, e.g. social factors such as public acceptance data would add a new dimension to site selection assessment. Also, ownership of the land is not included in this study.Social acceptance data might be particularly useful if land is held in private ownership. In addition to the radiation levels, also temperature affects the production capacity of PV cells (Carrion et al. 2008a; Carrion et al., 2008b) and could be considered as a potential factor. However, with new data included pairwise comparisions would need to be recalculated, causing the change of previously generated weights for each criterion.

Slope estimation from DEM is always a potential source of error as it differs to a certain extent from the field-measured slope.

Calculations made using Area Solar Radiation tool to estimate incoming solar radiation were based on default values for a generally clear sky. Therefore, possible cloud cover has not been taken into account in the radiation calculations.

No site visits were conducted in this study. Potential optimum sites can be assessed comparing Google Earth satellite imagery with Bing Maps aerial photography. This poses a risk that some characteristics of the study area such as vegetation and manmade features may have changed and do not exist any more as captured in the datasets and imagery.

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7. Conclusions

The study indicates the presence of multiple suitable sites for utility-scale PV development in county Kilkenny, Ireland. The chosen GIS-based MCDM methodology was found to be effective in identifying suitable sites and can be recommended for the future studies. The hierarchical structure of AHP is for everybody easy to understand and the calculation of weights could be easily modified should any changes occur. The results of the study are higly dependent on the restriction factors, which may be subject to change.

Following conclusions can be drawn from the results:

- Suitable areas for utility-scale solar PV farms with an area >10 ha cover 0.67% of the study area. The locations of suitable areas are mostly scattered in one corner of the county, in northeast.
- The northeastern corner near Castlecomer town is situated on upland Castlecomer Plateau, exemplifying how elevation influences incoming solar radiation. The terrain of the plateau is considerably higher than the surroundings but remains relatively flat.
- The most limiting factor for PV solar installations in the study area was found to be incoming solar radiation.
- Energy generation from solar PV is possible in county Kilkenny and has a high potential. Renewable energy usage in Republic of Ireland would increase by 24.85% if solar farms were set up at all suitable locations.
- As solar parks can be installed, and also de-installed, very quickly, this advantage can be taken to enable to meet renewable energy targets for 2020.

Since the study faced a number of limitations, it is recommended to extend future studies related to solar parks site assessment in Republic of Ireland with additional datasets. The main relevant dataset I would propose to use if possible is transmission lines data.

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