UTILISATION OF BROWNFIELD SITES FOR RENEWABLE ENERGY GENERATION IN BUILDING SUSTAINABLE CITIES

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Abstract

‘Sustainable city’ is a goal of how cities are developing to overcome climate change. Many countries develop their cities sustainably in various aspects including population growth, food production, sanitary and water treatment, residential planning and energy production. Although all aspects play important roles, energy is the key to powering all nations. Equipping sustainable cities with renewable energies can enhance the resilience of energy supply and halt climate change. To promote efficient land use, this research focuses on combining sustainable energy production with land reuse, making use of available brownfields land. It identifies potential brownfield sites to be developed for solar, wind and heat energy harvesting by employing the multicriteria decision making method (MCDM) combined with geographic information system (GIS). Three criteria were identified relevant for solar PV and wind turbine installations, they are solar radiation, site size and flood risk zone for solar PV and wind speed, site size and slope for wind turbine. The importance of the criteria to development was ranked by experts in planning and renewable energy using the Analytic Hierarchy Process (AHP), a branch of MCDM applying free software, AHP-OS. This method was tested in the context of Greater Manchester. Using the ranking contributed by experts in the MCDM workshop, the criteria were weighted and applied in determining the potential of brownfield for development. In the case of solar PV deployment, it was found that using the Inverse Linear scale in the AHP-OS, the best results were produced with the highest group consensus and relatively low consistency ratio. The results were almost comparable to the results obtained using weightings consistent with literature, where solar radiation was assigned 50% weighting and site size and flood risk zone were assigned 25% weighting each. The Inverse Linear scale produced better results than the same set of weightings grounded from literature (50% for wind speed, 25% for site size, 25% for slope) for wind energy case. For ground source heat pump installations, sites with sandstone and conglomerate bedrock were preferred due to the high thermal conductivity level besides the preference for highly populated area. While identifying feasible brownfield sites for renewable energy development, this research also produced a transferable process model based on guidelines from the Department of Communities and Local Government combined with the steps taken in this research. The model can be adopted by other renewable energy planning projects in other locations to achieve a sustainable city goal.

Keywords: sustainable cities, sustainable land development, renewable energy, brownfield, solar energy, wind energy, ground source heat pump.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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The author, better known as Harry Radzuan, received his first Honours degree in Electronics Engineering from the Infrastructure University Kuala Lumpur with an upper second class. After graduating, he worked as a Failure Analysis Engineer at Intel Corporation, a multinational organisation manufacturing microprocessor.

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Chapter 1 : Introduction

1.1 The Urbanisation Process and Shift to Sustainable City

On a global scale, humans use a lot of land that directly impacts the environment and how our life is structured. The usage of global ice-free land surface is estimated to be as high as 72% of the total 130 Mkm^2, leaving only around 28% of it unused (Cornelius, 2019). In a publication by the World Wide Fund for Nature (WWF), the used land is categorised into forest and extensive pasture (19% of overall usage each), savannahs and shrublands (16%), cropland (12%), intensive pasture (2%), plantation forests (2%) and infrastructure (1%), leaving the unused portions as other lands (12%), grasslands and wetlands (7%), and intact forests (9%) (Ibid.).

Despite the seemingly low percentage of land use for infrastructure that comprises of where we live, work, travel, commute and do our leisure activities, the number of populations grow year after year. The highly populated areas contribute directly to the high amount of carbon footprint. This is the case in urban areas with many tall buildings, residences and offices.

Today, 55% of the world's populations reside in urban areas. The gradual shift of humans from rural to urban areas is an ongoing process that is expected to increase the world's urban population to 68% by 2050 (UN, 2018). This growth is a projected combined value with an overall growth that would bring 2.5 billion people to urban areas by 2050. Additionally, 90% of the increase is in Asia and Africa, due to Asia being the home to 54% of the world's urban population, followed by Europe and Africa with 13% each (Ibid.).

With the ever-growing population of the urban areas, there have been concerns regarding the sustainability of many cities (Lee, et al., 2016). These issues include the supply of food, energy, clean water and waste disposal (Siemens, 2019). As a result, vacant land in the countryside may be turned into croplands to grow food for the urban populations, natural fossil-based energy sources will be quickly consumed, and the supply of clean water for the urban population will be insufficient; all of these contribute to major sustainability issues.

The importance of embracing and materialising the concept of sustainable cities can be seen all over the world. The impact of our modern city life has harmed our generation in various ways including the extinction of flora and fauna and environmental pollution. According to the UN-Habitat (2016) report, cities are responsible for 70% of global CO_2 emissions, resulting from the use of resources such as fuels, minerals and metals, as well as food, soil, water, air, biomass and ecosystems (Ameen & Mourshed, 2019; UN-Habitat, 2016).

The problem can become more serious as 75% of the world's energy consumption is in cities (Muneer, et al., 2011). According to research, the energy demand will grow by 40-50% by 2030 (Hake, et al., 2016; FAO, 2014; US NIC, 2012). If the predicted trend continues, cities will not be able to grow sustainably if they are not prepared. This global energy crisis, coupled with the climate change issue, demands cities to run more sustainably. In order to be sustainable, a city needs to survive without running out of resources. To prevent further problems from taking place, organisations around the world are seen to have taken measures to provide supplies for their population while curbing environmental pollutions.

For example, the United Nations have established a set of Sustainable Development Goals (SDG) that consist of 17 items in various aspects of life to ensure a better global future (depicted in Figure 1.1) (European Environment Agency, 2019). Three highly related items can be seen in the pie chart which are item 7: affordable and clean energy, 11: sustainable cities and communities and 13: climate action. These three items are basics for the place we live in.

Figure 1.1: United Nations' Sustainable Development Goals (Jill, 2020).

In item number 11: sustainable cities and communities, the sustainability level of a city is partly determined by the land use in the city. Due to the low percentage of natural land available (Cornelius, 2019), the way we use/reuse our land is critical. The inconsistent focus of industry causes some industrial areas to be abandoned and other land areas to be developed. This type of development that unnecessarily use up fresh land is not sustainable. However, if abandoned land is redeveloped instead, this can help to lower the grassland conversion simultaneously preserving our forests and natural land surfaces. There will also be a chance for used forests to be restored alongside the ecosystem.

The SDG can be achieved by importing food to ensure there is continuous food supply and there is no hunger, ensuring clean water is supplied to rural areas facing water difficulty, and integrating renewable energy (RE) in the energy production mix to ensure clean energy is available. Different types of RE can be obtained from within nature, whether directly or indirectly; these include wind, solar, hydro, sea wave, geothermal, gas and biomass (energy from waste, animal biomass and plant, ethanol) (BEIS, 2018; US EIA, 2018). All of these have been part of the RE sources in many countries.

RE are the type of energy sources that can self-regenerate and will always be readily available for use (Office of Energy & Renewable Energy, 2017). However, some types of RE are weather dependent which can cause intermittent supply, but when combined, they can provide us with a continuous energy supply. This is in line with the decarbonisation of energy objective employed in many countries to reduce carbon intensity (Robinson, 2017; WSP Parsons Brinckerhoff, 2015; Grantham Institute, 2014).

In the effort to tackle the energy supply problems and shift to RE, it is key to consider the locations of where the RE is to be installed. With the urban sprawl and overpopulation in cities, the high energy demand in those areas needs extra attention from planners and authorities when deciding new RE sites. Besides having to be located nearby areas with high energy demand, the production of such energy needs to be sustainable and efficient.

The expansion of RE usage has brought its cost down and allowed it to be more accessible (Arup, 2019). With the advantage of low RE cost and space availability in many buildings, built infrastructures can now be converted from being passive energy consumers to energy ‘prosumers’ (**pro**ducers+con**sumers)**, letting them earn money from their contribution back to the energy grid while generating energy simultaneously.

Besides the vastly available rooftop spaces on buildings, available brownfield land in and around conurbations can be another option for energy generators. Brownfields, sometimes defined as abandoned land or derelict land, exist as a result of deindustrialisation from traditional industrial activities over the years. This type of land is usually found in industrial areas of cities, such as abandoned factory sites or commercial areas in countries including the United States (US), the United Kingdom (UK) and all over Europe (Franz, et al., 2006). Today, brownfield land represents a lucrative, but largely untapped land resource (Thomas, 2002; Rafson & Rafson, 1999; Dennison, 1998).

Building on the sustainable city concept and the environment and energy crisis, it is important to address these global issues. Therefore, this research explores the potential of using brownfield land for RE generation to aid the development of a sustainable city and a more effective energy production.

1.2 Research Aim and Objectives

In the everyday context of our life, energy is an integral element that enables us to continue living. Most of human activities, such as cooking, heating, cooling, transporting, food production, powering machineries, communicating, will not be possible without energy as it is vital in powering up the nation (WCED, 1987). With the ever-growing population and demand for energy especially in modern cities, sources of energy are getting scarcer before being extinct. Realising this fact, the motivation and interest of this research grew to uncover the opportunity of deploying more RE that are available throughout the year.

This research proposed to diversify the usage of brownfield sites for RE generation based on the need to meet the electricity demand from various sectors. Previous study by Brown (2015) looked at the opportunity of transforming abandoned brownfield sites that are unsuitable to be redeveloped for housing and property into solar energy harvesting sites. Other research has shown that the issue of excessive availability of brownfield is a global problem, which can be caused by economic, environmental and social barriers (Thornton, et al., 2007).

Only some research has sought to compare experiences and lessons in developing brownfield for RE use. This is an important gap to address if the high number of brownfield sites are not redeveloped and brought back to life. Hence, this research aims to investigate brownfield lands' potential to contribute to the delivery of sustainable energy production. This is achieved through five objectives:

➔ To understand the potential of brownfield sites for the development of sustainable cities and how they can be associated with RE;

- ➔ To understand and analyse public policy related to brownfield redevelopment, renewable energy and renewable heat advancement;
- ➔ To engage with experts in deciding the importance of criteria in brownfield site selection for RE;
- ➔ To identify suitable brownfield sites for RE development by undertaking a spatial analysis using GIS;
- ➔ To develop a process model to support the implementation in other cities or countries.

With the ability to apply the process model produced in this research and support the implementation of RE in other cities and countries, better urban planning can be put in place. Thus, available land can be used more effectively to reduce the development of grasslands and forests, simultaneously achieving the SDG.

1.3 Structure of Thesis

Chapter 1 introduces the subject and outlines the context, aim and objectives of this research. Chapter 2 discusses the concept and motivation of 'sustainable cities' followed by the issues facing brownfield land all over the world. The policies pertaining to brownfield development are also discussed.

In Chapter 3, RE is then introduced, whereby solar-based and wind-based energy being the focus. Policies from countries including the US, UK and the EU are reviewed and compared in determining their best practice with regards to the RE implementation. Chapter 4 then discusses the renewable heat available for deployment in Greater Manchester as the study area for this thesis. Heat-related policies are also discussed in this chapter.

In Chapter 5, RE models that are implementable in Geographic Information System (GIS) are reviewed and compared. This is intended to find the best model to be used in identifying locations for installations using parameters set. In Chapter 6, the methodology of this research is outlined, beginning with the conceptual framework followed by the process and steps in addressing the research objectives. Greater Manchester is also introduced as the study area for this research and the justifications of its selection.

Chapter 7 follows with the explanation of the site selection criteria, before Chapter 8 elaborates the process of identifying the prime sites using open-source environmental datasets. A model is built for each RE type to accommodate different criteria. Chapter 9 presents the spatial analysis results that indicate site development priorities based on different weightings. An evaluation/

discussion is also conducted to examine the effect of applying different weightings to the final scores, simultaneously validating the process.

In Chapter 10, a process model is proposed for future renewable energy site identification projects, building on guidelines provided by the Department for Communities and Local Government to identify suitable sites and techniques applied in this research. This process model illustrates how the procedure adopted in this research can be transferred and applied in other planning projects, regardless of time and location.

Chapter 11 concludes the thesis with a summary of how the research objectives have been met, the research key contributions, limitations and potential future work.

Chapter 2 : Brownfield Redevelopment and Policy in Building Sustainable Cities

2.1 Introduction

Chapters 2, 3 and 4 comprise the literature review of this thesis. Beginning with this chapter, literature was reviewed to better understand the dynamics of brownfield definition, development, and challenges. Later on, the technical review in Chapter 3 and 4 converged into the types of renewable energy (RE) and renewable heat (RH) available, which were relevant to be deployed on brownfield land. A specific emphasis was given to solar-based and wind-based energy. Policies were also reviewed following the technical aspect of literature in Chapters 2, 3 and 4 to comprehend the policies practised regarding brownfield redevelopment and RE deployment.

Chapters 2, 3 and 4 aim to address the first and second research objectives; to understand and explore the role of brownfield sites for the development of sustainable cities and how they can be linked to RE, and to understand and analyse public policy related to brownfield redevelopment, RE and RH advancement. The main context of the analysis focuses on England, the US, Denmark and Sweden, with some references made to compare other cities in Europe, including Germany and France. This was done to link the development of brownfield to the installation of RE and RH in those countries and assess best practices.

2.2 Brownfield Defined

Brownfield land constitutes a key aspect of conurbations due to their post-industrialised nature and previous development (Alexandrescu, et al., 2014). The definition of brownfield varies by regions. Generally, a brownfield site is known as any land or premises that have been pre-developed and are not currently fully in use, although it may be partially occupied or utilised (Alker, et al., 2000). Some included the criteria of brownfield as land that was previously developed for urban uses (Raynsford, 1998), while others suggested that it should have been urbanised or used industrially, and subsequently vacated and made available for some re-urbanisation (Duany Plater-Zyberk & Company, 1998).

It is still arguable that in the US, a brownfield is defined as a property, the expansion, redevelopment or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant or contaminant (United States Environmental Protection Agency (US EPA) 2019), although some others identify it as abandoned land affected by hazardous contamination due to industrial heritage (Gray, 2015; Adelaja, et al., 2010). To qualify as brownfield, the US EPA indicates that a site must be in urban areas (Alker, et al., 2000). In Denmark, brownfield simply refers to any land that has been affected by contamination (Oliver, et al., 2005). In Sweden, there is no official definition used as it is commonly understood as formerly used land that needs revitalisation or remediation before returning to nature (Heasman, et al., 2011; Oliver, et al., 2005).

In England, brownfield is defined as any land that has been previously developed, including derelict and vacant land, which may or may not be contaminated (Dixon & Adams, 2008; ODPM, 2000). This creates a challenge when it comes to granting planning permissions and brownfield development, as the contamination level of a particular brownfield site or the vacancy is not known or recorded. Excerpts of brownfield definition from various countries are summarised in Table 2.1.

Despite being defined in such a way, in the UK context, the extent of contamination that is acceptable for any land to be categorised as 'brownfield' has not been made clear (Ministry of Housing, Communities and Local Government, 2012; Scottish Environment Protection Agency and Natural Scotland, 2009). Before 2010, there were 200,000 hectares of contaminated land said to exist in the UK (NHBC, 2008; DETR/Urban Task Force, 1999). Since the introduction of the term in the UK planning policy in the 1970s, various features and development of brownfield have been used (Adams, et al., 2010).

Table 2.1: Brownfield definition in different countries (US EPA, 2019; Government of Canada, 2016; Umwelt Bundesamt, 2014; Dixon & Adams, 2008; Scottish Government, 2002; CLARINET, 2002).

Country	Definition
England	Any land that has been previously developed, including derelict and vacant land, which may or may not be contaminated.
Scotland	Same as England but includes the reuse of redundant buildings for new uses.
Germany	Unused or underused urban land with development potential.
France	Previously developed land (agriculture, harbour, industry, service, ore processing, military/defence, storage or transport) that has been temporarily or permanently abandoned following the cessation of activity and must be reclaimed for future use. Brownfields can be partially occupied, derelict or contaminated.

Table 2.1 (continued).

Country	Definition
United States	The property, expansion, redevelopment or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant or contaminant.
Canada	Abandoned, idle or underutilized commercial or industrial properties where past actions have caused environmental contamination, but which still have the potential for redevelopment or other economic opportunities.
Sweden	No official definition. Commonly understood as formerly used land which needs revitalisation or remediation before returning to nature.
Denmark	Land affected by contamination.

In England, the Homes and Communities Agency (2014) classify brownfield land into five categories:

- ➔ Vacant land and buildings;
- ➔ Derelict land and buildings;
- ➔ Land currently in use and allocated in a local plan;
- ➔ Land currently in use with known redevelopment potential but no planning permission;
- ➔ Land that is unused or may be available for redevelopment.

To further comprehend the relationship between the categories of land mentioned above with the definitions of brownfield, brief definitions of derelict, vacant and contaminated lands are discussed. Derelict land is simply defined by The UK Derelict Land Act 1982 as ‘land so damaged by industrial or other development that is incapable of being beneficial without treatment’ (Department of the Environment, 1995, p. 3). Meanwhile, vacant land is regarded as the consequence of the insufficiencies of the definition of derelict land, and by definition it is ‘land on which some previous productive use has stopped for a significant period of time’ (Handley, 1996, p. 6). Further categorisation of vacant land may include lands that may be contaminated, derelict or neglected. Contaminated land is defined by the UK Environmental Protection Act (EPA), 1990, s78A (2) as any land that:

a. Significant harm is being caused or there is a significant possibility of such harm being caused; or

b. Pollution of controlled waters is being, or is likely to be caused in which the local authority the land exists within is responsible for.

The definition provided by the US EPA is linked specifically to the effects of land contamination based on its current use and is concerned with the potential harm of living organisms, ecosystems, property and water. However, specifically for brownfield, it is traditionally divided into three basic categories (Franz, et al., 2006; Millar, et al., 2005; Dennison, 1998; Ferber, 1997):

a. Viable sites: the private market is already working toward redevelopment without help from the public sector. Sites like this are usually found in economically dynamic locations and have more advantages than risks.
b. Marginally non-viable sites: public sector funding is needed to develop this type of sites. The major reason could be contamination on the sites which lead to high remediation costs, poor infrastructure or access and low real estate prices.
c. Non-viable sites: overwhelming contamination or high economic constraint with non-strategic location can result in sites being non-viable for redevelopment. Public funding is necessary to bring these sites into new uses.

As a comparison, the viable sites would be able to generate profit when put to a commercial use, the marginally non-viable sites would just breakeven while the non-viable sites would bring loss if developed (Franz, et al., 2006).

2.3 Brownfield Redevelopment

Brownfield redevelopment has been widely recognised as an important aspect of sustainable land management. Besides the direct effect of reducing environmental hazards, sustainable land management can make cities more attractive, create more jobs, boost the economy and increase tax revenues (Limasset, et al., 2018; Krzysztofik, et al., 2016). Redeveloped brownfields are also more sustainable than greenfields, which should be reserved for agriculture (Bartke & Schwarze, 2015; Stezar, et al., 2013). Subsequently, the term 'sustainable brownfield regeneration' comes to an existence to balance the tensions between economic growth and environmental and social impacts (Franz, et al., 2006; De Sousa, 2005; Dresner, 2002). RESCUE (2003) defined 'sustainable brownfield regeneration' as applied within the EU as (Dixon, 2007, p. 2381):

… the management, rehabilitation and return to beneficial use of brownfields in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations in environmentally sensitive, economically viable, institutionally robust and socially acceptable ways within the particular regional context.

Some planners advocating land recycling and economic development practitioners even seek to turn brownfield into 'goldfields' (Perera, 2017; Kalette, 2007) considering the vast opportunity that brownfields can offer. Brownfield development in many cities in the UK has an unpredictable record of accomplishment in bringing extensive benefits. As argued by Raco & Henderson (2006, p. 500) that

... brownfield development itself will not guarantee to deliver extensive urban regeneration unless programmes are embedded within a set of development projects and policy agendas.

They further mentioned that a strategically planned set of agendas need to be the overarching aim to tackle the planning and environmental problems including brownfield availability. This resulted in the creation of the urban policy, planning guidance and housing programmes in supporting brownfield development in the UK (Schulze-Baing & Wong, 2012; Adams & De Sousa, 2007; DETR, 2000; 1998). This clearly illustrates the UK government's understanding of reutilising brownfield land as an attempt at sustainable development (Dixon, et al., 2010; Dixon & Adams, 2008). The effort taken was motivated by the initial review by Barker in 2003 that recognised the importance of utilising brownfield in future development as the most efficient use of available land. The recognition led to a raised tendency to promote housing development on brownfield sites (Schulze-Baing & Wong, 2012; Dixon, et al., 2010).

Due to the significance of property development in urban planning, the policy created mostly focused on residential use. Developers have been engaging with brownfield sites and most new residential developments occur on them (Ministry of Housing, Communities and Local Government, 2018; ODPM, 2005). As brownfield issues are broadly discussed in housing policy in the UK since the beginning of the implementation of the national brownfield policy with the aim to build a high percentage of new housing on brownfield (50% in 1995, then 60% by 1998), is it then difficult to find a policy that supports brownfield land uses other than housing (Schulze-Baing & Wong, 2012; Dixon, et al., 2010; Adams, et al., 2010; Thornton, et al., 2007; Adams, 2004). The target to reuse brownfield for housing development became important to the wider urban regeneration and influenced the housing policy agenda throughout the new millennium. Even until recently, the new National Planning Policy Framework (NPPF) that was set out in 2018 still promotes housing development on brownfield (Ministry of Housing, Communities and Local Government, 2019, p. 19).

Besides being developed as housing and properties, alternative uses should be pursued to diversify brownfield development, despite such development being claimed as not having a clear focus, especially in terms of sustainable development (Dixon, et al., 2010). Much research has outlined that brownfield regeneration can take on many different forms, including industrial (Taddeo, et al., 2012; Zhou, et al., 2010; E2 Inc, 2010), commercial (Newton, 2013; ACSF, 2011), residential, temporary uses such as parks and open spaces (Loures, et al., 2016; Florea, et al., 2013), or mixed uses (Martinat, et al., 2018; Woodyard, 2013). However, there is a lack of studies that focus on utilising brownfield land for RE uses and the reuse plans have not always met community needs (Martinat, et al., 2018; Scott & Kühn, 2012). This is particularly the case where redevelopment for housing is too costly.

To shift the focus of brownfield development and better meet community needs, society needs a better awareness on the benefits of brownfield redevelopment. Apart from supplying more residential properties, the redevelopment of brownfield is beneficial in the following aspects (DCLG, 2015; 2012; Henderson, 2015; Williams & Dair, 2007; Dixon, 2006; Dorsey, 2003; POST, 1998):

a. Preventing urban sprawl;
b. Keeping cities compact;
c. Reduce out-migration;
d. Improve urban environment;
e. Relieve development pressure in the countryside.

Another significant benefit of brownfield redevelopment is its ability to improve the economic conditions of nearby residents. Many jobs can be created in the public and private sectors with a little investment by the government, as exemplified in research in Illinois (Hamm & Walzer, 2007). In the case of redeveloping brownfield sites in deprived neighbourhoods, the needs of deprived communities can be addressed if the projects are embedded in a broader set of policy measures to channel the benefits to them (Raco & Henderson, 2006). Brownfield redevelopment can also be an alternative way to deal with sites with hazardous waste when brownfield is cleaned up before putting it back to use, as argued by scholars (Fitzgerald & Leigh, 2002; Simons & Winson, 2002; Hula, 2002; 2001). This is more resource-efficient from development and environmental perspectives.

In the UK, there is no strong encouragement and support for the RE generation on brownfield sites as a solution to the increased demand in both, as reported by Brown (2015), although a guidance by the government mentioned that RE should preferably be placed on brownfield sites when possible (DCLG, 2013). However, in the US, their EPA runs a program that encourages the development of RE projects on marginal and contaminated lands and provides resources to communities engaging in those projects (US EPA, 2014).

2.4 Challenges Facing Brownfield Redevelopment

Many studies explored the barriers and drivers to brownfield redevelopment which mostly are based on stakeholder surveys (Frantál, et al., 2015; Letang & Taylor, 2012), expert interviews (De Sousa, 2003; Adair, et al., 2000) and local case studies (Martinat, et al., 2018; Dixon, 2007). Despite the importance of redeveloping brownfield, it is key to acknowledge the challenges that can be faced by brownfield projects. They present barriers to local developments, contribute to urban sprawl, potential hazards to health and environment and become ground for neighbourhood crime and illegal activities (Frantál, et al., 2015; Kunc, et al., 2014). When located within proximity to residential areas, they may also contribute to socio-pathological behaviour to residents (Martinat, et al., 2018; Rizzo, et al., 2015).

One of the main challenges is to incorporate brownfield development within the larger framework of community planning (Lee & Mohai, 2012). For it to be effective, it must be underpinned by a range of social and infrastructure programmes and be people-focussed, to confront the inter-related problems affecting urban communities. This means that it requires the officials or authority to act on local issues that can lead to the success of the development projects. However, Raco & Henderson (2006) argued that the success is not merely a matter of 'reusing' urban sites, but also involves making decisions over what practical steps should be taken, what can be achieved from the projects and what sorts of end-use should be promoted.

From an economic perspective, brownfield projects can sometimes incur overbearing mitigation costs where it is necessary to bring the sites up to a safe standard, which may be more than what the land is worth after redevelopment. The costs may include site-specific risk assessment of contaminants, the deconstruction of existing buildings that cannot be reused and the remediation process itself. Such major costs would cause difficulty to developers to embark on new brownfield projects, even if the costs of cleaning and redevelopment are known with certainty (Limasset, et al., 2018; Bartke, 2011; Schädler, et al., 2011).

Brownfield development is a complex process that requires the knowledge of environmental agency regulations, knowledge of remediation procedures, the capacity to assess and limit liability, the ability to navigate complex financial vehicles, and the ability to manage projects to achieve the desired level within a given budget (Meyer & Lyons, 2000). With the challenges described, time and costs involved in the process can present disadvantages and hinder development. Furthermore, the development can pose risks in terms of execution, for example; site cleaning, inaccurate assessment result and going against regulations. In addition to risk-related challenges, local brownfield developments also might lack the expertise and capacity to handle such cases, besides investors that are impeded with the fear of liability of site clean-up. These ‘development frictions’ could be a bigger challenge when there are unexhausted greenfield supplies available on the edge of a city (Dewar, 2008; Walzer & Hamm, 2005).

The homogeneous focus of brownfield development for housing as exemplified in the UK is also another hindrance to the diversification of development purposes. There is a possibility that city planners and municipalities are not aware of the prioritisation tools that exist (Ivana, 2018). One main reason behind this could be the application of such managerial tools for brownfield prioritisation that are still not widespread (for example, sYstem for Regional rIsk Assessment of Degraded land (SYRIADE), Timbre Brownfield Prioritization Tool (TBPT) and Holistic Management of Brownfield Regeneration (HOMBRE) (Limasset, et al., 2018; Martinat, et al., 2018; Alexandrescu, et al., 2017). With better awareness of such aids, planners can better select and justify the purpose of development rather than sticking to the norm.

In terms of sustainability, research at a national level in the UK shows that industry struggled to come to terms with ‘sustainability’ and how to integrate the concept within brownfield regeneration (Dixon, 2007). One development, for example, may appear to be sustainable in bringing a derelict site back into use, but it may also impose adverse effects on the economy, environment and social wellbeing of neighbouring sites and communities. This may happen in a case where a development with a sustainable intention may begin with a construction that temporarily disturbs the neighbourhood and cause minor pollution. Such a case might happen if the regeneration is ‘property led’ and focused on commercial, industrial or housing projects to attract more investors and visitors. The reassessment of environmental impact resulting from brownfield redevelopment is also a challenge, especially in changing the perceptions of communities, developers and government officers (Ribeiro, 2007; Raco & Henderson, 2006).

Despite many reasons that can hinder brownfield regeneration, ownership constraint is one significant factor. It is said to exist if development is unable to proceed due to the obstruction in acquiring ownership rights rapidly through normal market processes (Frantál, et al., 2013; Dixon, et al., 2011; Longo & Campbell, 2007; Adams & Hutchison, 2000). The case might be compounded when the lands to be redeveloped are owned by multiple individuals. Hence it is recommended that significant ownership constraints be resolved before brownfield development is carried out.

Additionally, in most countries, the mapping and inventorying of brownfield sites are not centrally organised. As a result, specific information or GIS data regarding brownfield land that plays an important role in aiding developments are not openly available. Furthermore, the data may be incomplete, inconsistent or developed using problematic methodology (Frantál, et al., 2013). This can cause more hindrance to brownfield developments, especially when the contamination status of brownfield is not available in the database. Where registers of brownfield are maintained by private companies and consortia of owners, they are often protected or provided with only limited information and poses more constraints to developments (Frantál, et al., 2015).

Research found that site-specific factors such as the size of brownfields, previous land use and land contamination do not act as barriers for brownfield regeneration in prosperous locations where there is a high demand for redevelopment for particular projects (Frantál, et al., 2013; Longo & Campbell, 2007). However, as mentioned earlier and will be discussed later in sections 2.5 and 6.4, there are still many brownfield sites available in England, particularly in developed regions. It is then the intention of this research to overcome the issues facing brownfield land and contribute to sustainable city.

From the information uncovered on brownfield and the issues faced, solutions should be continuously sought to ensure a sustainable brownfield regeneration. There has been growing policy emphasis on this matter which links the concept of sustainable development and brownfield regeneration (Dixon, 2006). In the next section, policies implemented in the UK, US and the EU with a specific focus on Sweden and Denmark, to develop brownfields are reviewed and critiqued to fulfil the second objective of the research in achieving the overarching aim. The countries for this review were chosen based on their policies practised to revive brownfield sites to compare best practices.

2.5 Brownfield Policies

Extensive urban regeneration cannot be achieved with brownfield development alone unless the programmes are embedded within a broader set of projects and policies. These need to take into account how to combine profitability, brownfield use and carbon reduction, three main areas that create uncertainties (Brown, 2015). In overcoming these uncertainties, a wide variety of financial, fiscal, legal, regulatory and policy incentives can be practised concerning brownfield redevelopment. Such incentives include brownfield tax credits, tax increment financing, brownfield redevelopment grants and loans and brownfield site assessment services (Adelaja, et al., 2010; Michigan Department of Environmental Quality, 2008). These incentives are important in eliminating the reluctance in redeveloping brownfield sites that are always associated with risks including the wrong location, cleaning up costs, high rehabilitation costs and low real estate value.

Research suggests that the sluggishness in brownfield redevelopment in some countries may be caused by the real or perceived barriers that outweigh the policies, tools and incentives in place, even in periods of rapid economic growth and sprawl (Adelaja, et al., 2010). In this section, several policies that drive the development of brownfield in various countries are discussed to help extract best practices.

In Europe, the EU structural funding is considered the most significant financial incentive that enables the regeneration activities in the EU countries without which, regeneration is only restricted to economically feasible sites (Thornton, et al., 2007). The Structural Funds originate at the EU level and are distributed at the national, regional and sub-regional level by organisations aiming to achieve the same objectives as stated in the EU guidance (Vanheusden, 2007). The proposals submitted for the fund are chosen based on the priority defined by the Commission, and they are meant to tackle several objectives:

- ➔ Supporting development in the less prosperous regions;
- ➔ Redeveloping areas with structural difficulties;
- ➔ Development of human resources.

At present, five structural and investment funds exist in the EU that may impact the extent of brownfield development. They are the European Regional Development Fund (ERDF), European Social Fund, Cohesion Fund, European Agricultural Fund for Rural Development and European Maritime and Fisheries Fund, all of which with their own goals, objectives and regional limits (European Commission, 2019b). EU countries can take advantage of the available instruments to develop brownfield sites in the form of forums and research networks organised through the ERDF, which are (Ramsden, 2010):

1. INTERREG IV C: constitutes B-Team as a collaborative effort to influence existing and future policies on brownfield and address the issue of improving and transferring brownfield policies in partner regions and beyond;
2. URBACT II: realising the potential of abandoned military sites to bring them into use in vibrant cities;
3. INTERREG III: six partner countries came together to share experience and develop innovative approaches to regenerating brownfield;
4. LUDA: brought six cities and ten research institutes to conduct interdisciplinary research;
5. NICOLE: a forum where industry, service providers and academia cooperate to manage and develop contaminated land;
6. CABERNET: to address the complex multi-stakeholder issue raised by brownfield regeneration;

7. SNOWMAN ERA-NET: cooperative research on sustainable soil pollution management with partner countries Austria, Belgium, France, Germany, Netherlands, Sweden and the UK.

The ERDF also supports the development of tools related to brownfield redevelopment. Some tools were developed to assist planning authorities to identify the cause that should be prioritised for brownfield development. These tools include the Spatial decision support sYstem for Regional rIsk Assessment of Degraded land (SYRIADE) (Limasset, et al., 2018; Agostini, et al., 2012), Timbre Brownfield Prioritization Tool (TBPT) (Alexandrescu, et al., 2017; Bartke, et al., 2016) and Holistic Management of Brownfield Regeneration (HOMBRE) (Menger, et al., 2013). Although such aiding instruments exist, they are still not widely known or used (Limasset, et al., 2018; Alexandrescu, et al., 2017). It can be noted that countries such as Sweden and Denmark are entitled to the ERDF due to both countries' membership with the EU, despite the difference of their brownfield definitions.

Thornton et al. (2007, p. 126) proposed that brownfield-related policies to consider regional conditions, especially in regions with a large stock of highly contaminated brownfields or a weak real estate market where brownfield regeneration requires a higher level of incentives. They also proposed that the European Commission to encourage and support brownfield redevelopment projects in all affected EU countries and for local authorities that work on sustainable brownfield regeneration to be established. Following this idea, one proposal was presented to the EU Commission to prevent soil contamination as an integrated EU policy. The purpose is to limit the intentional or unintentional introduction of dangerous substances to the soil and to control soil degradation and its level to avoid risk to human life and environment and to guarantee food safety (EUR-Lex, 2019; Vanheusden, 2007). However, after being pending for almost eight years without a majority support, the commission withdrew the proposal, opening the way for alternative initiatives (Pérez & Sánchez, 2017).

It is a contrasting situation in England, where urban policy, planning guidance and housing programmes exist and in favour of brownfield development, as reported by the Department of Environment, Transport and the Regions (DETR) (2000a, 2000b, 1998). Policy requirements to develop those sites to be sustainable also existed in addition to develop a large number of brownfield sites. This was intended to have a growing number of sites that are sustainable on their own, besides contributing to the strategic urban development patterns (Williams & Dair, 2007). The sustainability principles were all stressed in the national planning guidance on sustainable development (ODPM, 2005), with the main aim of not only to regenerate individual sites and their neighbourhood, but also in the wider policy context to curb urban sprawl and reduce the loss of agriculture and rural land in a sustainable way (Schulze-Baing & Wong, 2012; Spaans, et al., 2011; Dull & Wernstedt, 2010; Longo & Campbell, 2007).

The National Planning Policy Framework (NPPF) formulated by the central government provides guidelines for local authorities. It also has a strong emphasis on the utilisation of brownfield in different aspects, mainly to protect greenbelts and contain urban sprawl (Ministry of Housing, Communities and Local Government, 2019). Parallel to that, a brownfield land register should be established and maintained by local planning authorities or other plan-making bodies as part of the government regulations to identify brownfield sites of various ownerships, to facilitate development opportunities and to keep track of their development progress. To date, there are approximately 66,000 hectares (ha) of brownfield sites in England (Gray, 2020). As fresh land availability reduces, governments have been putting efforts in redeveloping them in support of the sustainable development. It is considered as vital in improving the conditions of the environment and economy of nearby residents (Lee & Mohai, 2012).

In the US, the incorporation of the Environmental Protection Agency (EPA) in 1994, including brownfield initiatives evolved into a national programme that altered the way contaminated land was perceived, addressed and managed (Thornton, et al., 2007). This achievement was made possible by the Small Business Liability Relief and Brownfields Revitalisation Act, which transformed EPA's policy into law in 2002 (Guariglia, et al., 2002; Mitchell, 2002). The act is the most comprehensive package since the Superfund Amendments and Reauthorisation Act of 1986 (SARA). Solar generation on brownfields received the third-highest incentive level under the Solar Renewable Energy Certificates (SREC II) programme in the US, making it more highly valued than greenfield and rooftop generation (Goodbody, 2016).

Despite being described as 'problematic areas' by authorities and require financial and political intervention (Hartmann, et al., 2014), a broad agreement still exists among professionals regarding the vitality to develop brownfield instead of greenfield. However, there are barriers and risks linked to that, leading governments to initiate brownfield remediation programmes. Many countries such as Germany and Canada offer such programmes (Pippin, 2009), yet, the US EPA was said to stand out by providing several best practices for redevelopment (Hartmann, et al., 2014; US EPA, 2012; NALGEP, 2012).

Beginning with small amounts of seed money to boost brownfield projects in the mid-1990s, hundreds of projects were launched due to the grants supplied. Later in 2002, many of US EPA's practices, policies and guidance were codified under the Small Business Liability Relief and

Brownfields Revitalization Act, enabling the EPA to further expand their assistance to the public and private sectors in promoting brownfield reutilisation. And most recently in 2018, the Brownfield Utilization, Investment and Local Development Act re-authorised EPA's Brownfield Program, giving them the authority on changes that affect grants, ownership and liability provisions of brownfield (US EPA, 2019).

Besides financial and political intervention by the government as described by Hartman et al. (2014), ownership constraints can also be resolved with purposeful interventions, where they may assist brownfield projects to commence with ease. An ownership constraint is said to exist if development is hindered due to the ownership rights that cannot be acquired through normal process. As research claims, multiple land ownership demonstrated to be the most harmful to urban redevelopment (Adams & Hutchison, 2000). The intervention is not only limited to properties with ownership constraints, but also in acquiring usual formerly used properties as developers/investors tend to purchase free open spaces that are ready to use, even with incentives (Thomas, 2002).

In a study by De Sousa (2005), their interviewees identified policies related to the provision of project grants to be the most critical, as it helps the projects to commence. Whereas other financial incentives were equally critical as they provide a significant amount of funding. Their responses also revealed that local government to be the most important facilitator for the completion of brownfield projects, and they should be more proactive in inspiring and supporting developments. This was further seconded by several interviewees claiming smaller jurisdictions to be particularly effective as they have a greater desire to overcome brownfield problems. The idea is sustained by Hamm & Walzer (2007) who describe the capability of local authorities in making crucial differences that can lead to a project's success.

De Sousa's (2005) interviewees also assessed the US federal government's role in making a change to existing regulations, increasing funding for clean-up and attracting the media to brownfield issues. This is especially true when greenfield sites are readily available by the edge of a city, which might be more attractive to private investors (Hamm & Walzer, 2007; Walzer & Hamm, 2005), as the ease of investing and developing greenfield would be more economical than reviving abandoned brownfield land that might need to be remediated. To aid brownfield redevelopment, governments need to work on changing negative perceptions of communities, developers and other officers regarding the disadvantages of a high number of undeveloped brownfield sites to stimulate their regeneration besides tackling specific technical and contamination problems (Raco & Henderson, 2006).

The contaminated brownfield sites will bring no benefit if left unremedied; instead, they will just be an eyesore to the neighbourhood and the contamination remains. With regards to policies that need to be implemented, procedural sluggishness should be overcome by, for instance, speeding up the application process for brownfield regeneration, increasing funding for remediation and redevelopment and providing more assistance at the early stage of the site assessment (De Sousa, 2005).

The creation of new policy and regulation should be in place if there is an intention in changing the way the private market behaves. There is also debate on whether a more thorough public intervention can expand the level of brownfield development. In short, brownfield-related incentives that are offered in the EU, the UK and the US include (European Commission, 2019b; 2016; Goodbody, 2016; Hartmann, et al., 2014; Thornton, et al., 2007; De Sousa, 2005; Adams & Hutchison, 2000):

1. Brownfield tax credits;
2. Tax increment financing;
3. Central structural funding;
4. Good remediation programmes;
5. Reduce procedural sluggishness;
6. Resolving ownership constraints;
7. Brownfield redevelopment grants;
8. Attract media to brownfield issues;
9. Brownfield site assessment services;
10. Encouragement and support for projects;
11. Developing brownfield national programme;
12. Develop policies that link to the provision of project grants;
13. Intervention in professional services by providing technical support and advice;
14. Changing the way contaminated properties are perceived, addressed and managed;
15. Changing negative perceptions of communities, developers and officers toward brownfield.

2.6 Summary

This chapter discussed the existence of brownfield land and its relation to the urban environment. There are various policies created revolving around brownfield regeneration as an effort to revive and sustain conurbations, some of which include financial, fiscal, legal and regulatory. In the UK, there are guidance and planning policies implemented for brownfield. There is also debate on whether public interventions will improve the level of brownfield development.

Different strategies established for different brownfield sites can bring many advantages, and the benefits gained are not just locally but also regionally (Raco & Henderson, 2006). Moreover, the central government has the power and authority to encourage public-private partnerships when local authorities face any difficulties (Dixon, et al., 2010). Despite the successes that most policies have achieved with regards to brownfield and RE, there is need for ongoing innovation in policy and regulation if any change is required in the way the private market behaves (Adams, et al., 2010).

Although governments and investors should be aware that the benefits of brownfield redevelopment can take several years to accumulate, the longer-term gain should not be underestimated. This translates into a long-term uncertainty and risk, where mitigation plans need to be considered. Besides that, other risks such as investment risk can be reduced by governments by leveraging public funds and private money through subsidised insurance, waivers of development fees, regulatory relief, property tax reduction and public investments (Medda, 2013).

The next chapter focuses on the available RE in the urban context, with special attention on solar- and wind-based energies. Both are the focus of this research as they can contribute to building sustainable cities. Their working principles, deployment strategy and related policies are discussed in detail in Chapter 3.

Chapter 3 : Renewable Energy in the Urban Environment to Build Sustainable Cities

3.1 Introduction

This chapter forms the next part of the literature review focusing on the technical details of renewable energy (RE) applicable in the urban environment. To address the first and second objective, this chapter looked at solar-based energy, wind energy, their working principles and some examples of their deployments in various places. A later section of this chapter focused on urban wind turbine (WT); a type of turbine suitable for installation in urban areas. This was to determine potential types of RE to installable at brownfield sites. Later on, policies related to RE deployments were reviewed. As done earlier in Chapter 2, the technology reviewed were related to policies in England, the US, Denmark and Sweden to assess best practices that can be adopted in other places.

3.2 A Shift to Renewable Energy in Europe

Generating and consuming energy is crucial for the economic development. Natural resources, for example, oil and coal can easily be obtained from the ongoing activities of mining and offshore petroleum extraction. With the growth of the global population, research suggests that global energy demand will grow by more than 33% by 2035, with the highest demand being in developing countries such as China, India and in the Middle East. They represent more than 60% of the total increase in demand (Martinopoulos, 2016; Sánchez-Lozano, et al., 2016; Ullah, et al., 2013).

To combat the exhausting supply of traditional energy resources and environmental concerns (Firozjaei, et al., 2018; Jahangiri, et al., 2015), energy needs to be used more efficiently and generated sustainably as it is an essential commodity for the ever-increasing world populations. According to a projection based on the ratio of reserve to production of fossil-based fuels, global oil, natural gas and coal will only be able to supply the world for 50, 51 and 132 years respectively (BP, 2019). Another prediction states that the Middle East, as the major producer and exporter of natural gas, will face an energy crisis if they run out of crude oil (Jahangiri, et al., 2016). Without any contingency plan, power generation and supply could come to an end when these natural resources become extinct.

There are various forms of RE that are naturally clean, can be automatically replenished and do not leave any carbon footprint in usage. Geothermal, biomass, solar, hydro, ocean, wind and hydrogen are types of existing RE widely used around the world (Claes, 2016). However, the availability and suitability of each type of energy may depend on the geographical location. This challenges a country or city in identifying their suitable RE mix. For example, in a country with many rivers, hydropower will be a potential RE, so long as the rivers do not become dry. Similarly, only countries that have access to the shore and ocean can opt to harvest the ocean energy.

In the case of solar energy, the locations for the placement of the collector systems must be carefully studied to achieve maximum efficiency. Countries located close to the equator receive higher solar radiation compared to countries closer to the poles (Renné, 2016). For instance, Quito, Ecuador which is located on the equator (-0.179° S) receives an average of 2,079 kWh/m^2 of annual solar radiation while Berlin, Germany (52.520° N), located in the west of Europe, receives 1,052 kWh/m^2 of annual solar radiation. Meanwhile, Manchester, UK (53.481° N), receives a solar radiation of 912 kWh/m^2 annually (SolarGIS, 2017). Despite the lower amount of radiation received in the north, Manchester can still benefit from the solar radiation available. Additionally, the strategic location of the country gives it excessive opportunity to be utilising other types of RE technology (European Environment Agency, 2009a).

For a city to achieve its ambition of becoming sustainable and realise its carbon footprint reduction targets, there needs to be proper spatial planning of the harvesting, distribution and usage of RE. Moreover, fossil-/carbon-based reduction target and public awareness and encouragement should be in place. Relevant policy to support the idea is also needed to assist and make the most of the available RE (Brown, 2015). Other ambitious cities in the world are already sustainable or running fully (or majorly) on RE. Freiburg, Germany for instance, has been encouraging its residents to use public transport by practising different policies and initiatives during the past few decades. Private transportations that emit carbon dioxide and pollute the air has been reduced by implementing policies that discourage the ownership of private vehicles and promote the use of electric public transports such as trams and buses (Mössner, 2016; Buehler & Pucher, 2011).

In terms of RE generation in the European Union, Sweden generated 53.8% of the total in 2016, marking the highest generation in the EU, followed by Finland (38.7%) and Latvia (37.2%). The United Kingdom generated nearly 10% of the total EU generation by RE, almost at a similar level with Ireland and Cyprus, illustrated in Figure 3.1. Proxy 2017 indicates values estimated for 2017 based on previous values. Table 3.1 shows the RE generation in Nordic countries as compared to Germany and the UK.

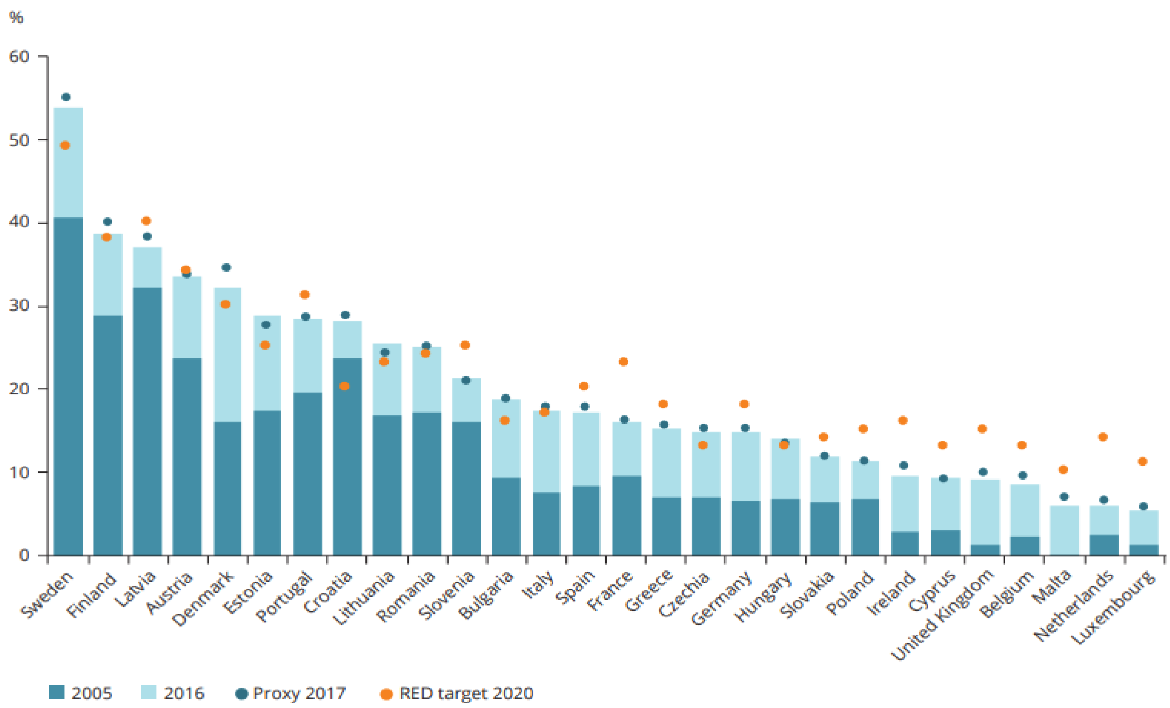


Figure 3.1: RE shares by countries in the EU (European Environment Agency, 2018; Eurostat, 2018; European Environment Agency, 2017).

Table 3.1: RE generation by countries in 2017 (Energinet, 2018; Burger, 2018; Statistics Norway, 2018; SCB, 2018; Sweden.se, 2018; BEIS, 2018).

Country	**RE Generation (GWh)**	**Percentage of RE/ total energy production (%)**
Denmark	19,597	67
Sweden	160,481	54
Germany	210,000	38
United Kingdom	27,900	30

From the vast utilisation of solar, wind and hydro energy in leading countries in Europe, a projection for the European energy mix for 2020 estimated that solar and wind energy will become significant power generators (Gatzert & Kosub, 2016). They will benefit the rural off-grid areas, as energy harvested directly from nature are the best solution for a decentralised energy supply. Due to the nature of brownfield sites that are the focus of this study, solar and wind energies are discussed in this chapter as the main RE to be deployed.

3.3 Solar-based Energy

Based on the increasing installations of solar energy systems globally, solar energy is one of the most favoured non-fossil-based energy systems. This is due to the scarcity of fossil supply over the years (Hasnain, et al., 1998; Charters, 1992; Bourdiros, 1991). Its abundance in nature and availability throughout the year in most places are the primary reasons that it tops the list of RE technology, comparing against wind, geothermal, hydro and wave (Sen, 2004). Most of the landlocked countries without access to oceanic energy are still able to harvest solar radiation to generate electricity, heat water and provide in-building heating and cooling (Wang, et al., 2016).

Solar energy can be considered as one of the best sources of RE that gives the least adverse effect to the environment. Twelve significant advantages of solar-based energy are (Buker & Riffat, 2015; Mundo-Hernández, et al., 2014; Solangi, et al., 2011):

1. Natural resources will not be depleted by using solar energy;
2. No greenhouse gases emitted (particularly carbon dioxide and nitrogen oxide/dioxide);
3. No toxic gases will be released (sulphur dioxide, particulates);
4. No liquid or solid waste products are produced;
5. Reduced transmission lines from the grid (if used as stand-alone);
6. Diversification and security of energy supply;
7. Meet energy demand while maintaining ecosystem balance;
8. No noise is produced while electricity is generated;
9. Solar energy technology has a long lifespan of about 30 years;
10. Use and disposal of the silicon used in photovoltaics (PVs) are not harmful to the environment;
11. PV modules can be recycled to reduce energy consumption in production;
12. PV modules require low maintenance.

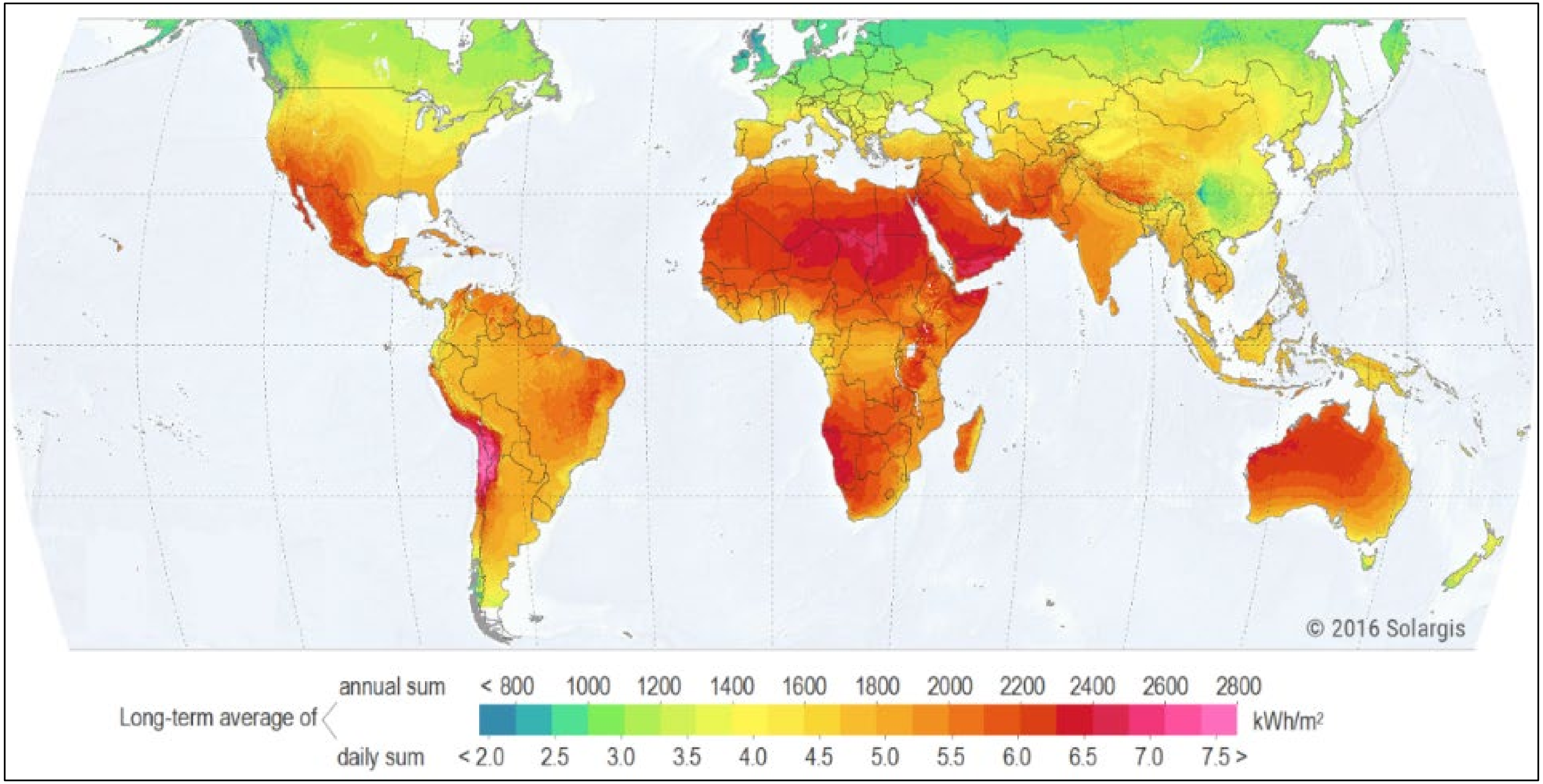
One way to utilise solar energy is by using the thermal energy from solar radiation as a source of heat. This type of system is known as the solar thermal system (Wang, et al., 2016). It is especially useful in domestic hot water systems, power heat engines and to power refrigerators and air-conditioners. Another way to use solar radiation is to capture photons from the sun to generate electricity for general usage, which is done through solar PV (Sen, 2004). The working principles of solar water heating and PV were studied to compare their advantages and the scalability of each technology for this research following the discussion on solar radiation below.

3.3.1 Solar Radiation

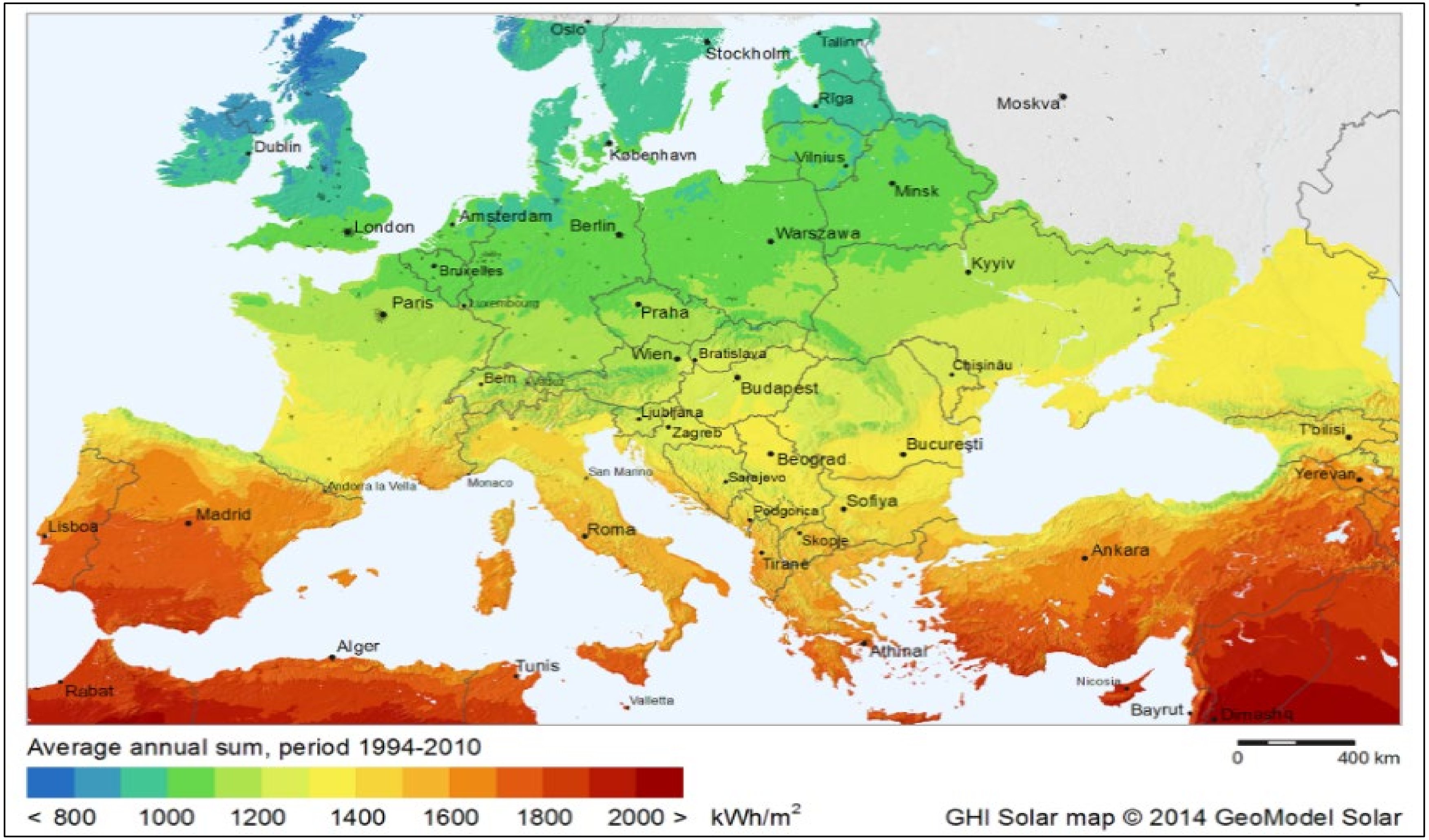
There are two types of solar radiation; direct normal irradiation/ irradiance (DNI) and diffuse horizontal irradiation/irradiance (DHI). DNI is the sunlight that penetrates the Earth's surface and directly hits a perpendicular surface, whereas DHI is the scattered light that hits a surface from various angles. The relative proportion of direct to diffuse radiation depends on the time of the day, time of the year, meteorological conditions and surrounding sites. This means it could be diminished by clouds, dust or gasses after entering the troposphere (Sen, 2004).

Global horizontal irradiation (GHI) is the total amount of shortwave radiation received by a surface horizontal to the ground from the sky. The value of GHI includes the value of DNI and DHI. It is also a reference radiation for the comparison of climatic zones (SolarGIS, 2017), as shown in Map 3.1. In this research, GHI is used to compare the annual solar irradiation in different countries as it is a useful parameter for solar PV.

As seen in Map 3.1, the closer the locations/countries to the equator, the more sunlight they receive. This radiation is shown as annual sum and daily sum, in kilowatt-hour per square metre (kWh/m^2). The highly-radiated areas which are marked in dark red/maroon range between 2000-2500 kWh/m^2 annually. These areas include Africa, Australia, parts of North America and parts of South America. Although the areas in the green and yellow zones receive around 900-1600 kWh/m^2 annual solar radiation (Map 3.2), the opportunity of exploiting solar PV is still prominent and should not be wasted.



Map 3.1: World Global Horizontal Irradiation (SolarGIS, 2016).



Map 3.2: Global Horizontal Irradiation for Europe (SolarGIS, 2016).

The UK receives a moderate amount of sunlight, ranging from 900-1,300 kWh/m^2 per year depending on location, with an average of 1,000 kWh/m^2 (SolarGIS, 2016). Even though the solar radiation in the UK seems slightly lower than other European countries such as Germany, Italy and Portugal, a typical 4 kWp PV system could contribute to a saving of 1,670 kg of carbon dioxide a year in Manchester and 1,900 kg in London (Energy Saving Trust, 2014).

Despite all the positive and progressive steps taken by some countries and growing interest in some others, many studies that involve previously developed land or contaminated sites were reportedly focused on bioenergy and disregarded more widely available sources such as solar and wind energy (Niblick & Landis, 2016; Cowell, 2010; Sørensen, 2001). Studies show that the locations of solar and wind farms are often in rural areas, which demand far less energy than the urban areas (US Dept. of Energy, 2015; 2012), thus causing higher energy transmission cost and greater loss of energy. Typically, the loss that occurs in energy transmission and distribution is around 6% (World Bank, 2015).

Concerning this research, as solar farms are proposed to be built on brownfield land, the distribution of the utility-scale solar plants (facilities that supply to the grid) are not solely reliant on areas with high solar radiation. The deployment at areas with lower solar radiation is possible, as evidenced in studies in cooler climate regions (Klusáček, et al., 2014). The deployment of solar panels on brownfield grounds is favourable as it does not disturb the soil, making it a wise option for contaminated sites (Klusáček, et al., 2014; Ribeiro, 2007).

3.3.2 Working Principles of Solar-based Technology

i. Solar Thermal System

A direct solar thermal system uses a solar collector that captures sunlight and heat during the daytime using flowing water. This is widely used as the main apparatus for domestic water heating, for example, individual houses and swimming pool heating (Wang, et al., 2016). There are also other uses of solar thermal systems that can generate larger power, for example for crop drying purposes, to power up heat engines, refrigerators and air conditioners (Sen, 2004). Most of the generation and usage are local, which means the heated fluid in the system does not need to be transported a long distance. Seven types of solar collectors are (Wang, et al., 2016):

a. Concentrating type;
b. Non-concentrating type;
c. Low temperature: under 100°C;
d. Medium temperature: 100°C - 200°C;

e. High temperature: higher than 200°C;
f. Tracking collector: follows the direction of the sun;
g. Non-tracking collector: stationary.

Three types of collectors can fulfil the criteria above: flat-plate, evacuated-tube and concentrating collectors (Gunerhan, et al., 2008). For domestic water heating, flat plate collectors are mounted on the roof of a building with the need for hot water (Figure 3.2) (Sen, 2004). This type of stationary collector cannot track the sun; thus, the solar collector needs to be positioned to directly face the sun during the daytime to harvest maximum sunlight. The collectors are usually fixed to face south in the northern hemisphere and vice versa. But for low latitudes, the angle of the collector is almost equivalent to the angle of latitude but increases by 10° at 40°N and 40°S latitudes.

Most flat plate collectors use a black insulation back panel to ensure that the plate absorbs as much incoming heat as possible. An optimum utilisation can yield a typical temperature between 40°C and 80°C in the system, depending on the astronomical, topographic and meteorological conditions (Sen, 2004). However, there are three ways through which heat loss can occur: 1) conduction; 2) convection; and 3) radiation. Heat loss is a critical issue in hot water distribution, particularly if this system is implemented as part of district heating.

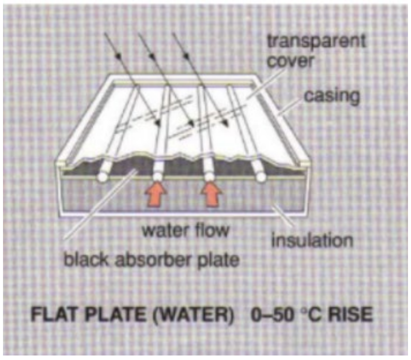


Figure 3.2: Illustration of flat plate collector (Sen, 2004).

To have sufficient and successful solar thermal production, it is always practical to have intense and direct sunlight conditions, for example as occur in the arid regions (Sen, 2004). This ensures the continuity and adequacy of solar energy to heat the flowing liquid. Due to the need of high and direct sun radiation for an efficient solar thermal system, this type of solar thermal system is not considered in this research as large-scale applications can cause a considerable heat loss.

ii. Solar Photovoltaic

Solar PV functions by capturing the photon radiated from the Sun using specially treated semiconductor materials. Physically, PV cells consist of two thin layers of semiconductor materials doped with different impurities and form a junction. The layer that is doped with the positive-type semiconductor is called the 'p' layer, while the negative one is called 'n', hence forming 'p-n' junction (Ohta, 1979). Because of the different doping in the pure semiconductor materials, the p-n junction provides a platform for electrons to move. This effect creates an electric field, which is then streamed through internal wires to be converted into electricity (Mohapatra, et al., 2012; Knier, 2008). There are different opinions on the dominant PV cell material in the market today. Some research claims that the multi-crystalline silicon which has an average efficiency of 15% dominates the market, (Lior, 2008), while others argue for monocrystalline or polycrystalline, which have a variable efficiency ranging from 12% to 17% (Mundo-Hernández, et al., 2014).

Like the solar heating system, it is necessary to have solar PVs tilted to face the sun. Theoretically, the tilt angle depends both on the latitude and the day of the year. In the summer months, it is advantageous to have the surface tilted a little more towards the horizontal; while the opposite in the winter months due to the height of the sun in the horizon. Sen (2004) suggested that PVs are much more effective in hazy or partly cloudy conditions than the solar heating system. This is because solar PVs are usually meant to be working under 25℃; which is why the standard test conditions by manufacturers usually quote that value. Under a hotter temperature, the PV performance would degrade (Richardson, 2018).

Countries that are widely utilising solar PV technology include Germany, the UK and the USA. Germany is unarguably the world leader in the development and generation of solar system and energy, which is particularly used to produce electricity and heat (Kylili & Fokaides, 2015; Solangi, et al., 2011; Park & Eissel, 2010). A few countries that deployed solar PVs were studied in terms of their installed capacity and amount of energy generated by solar PV.

Table 3.2: Installed solar PV capacity and generated energy in various countries (EurObserv'ER, 2020a; 2019a).

Country	Installed capacity (MW)		Energy generated by solar PV (TWh)	
	2018	2019	2018	2019
Germany	2,938	3,856	45.78	47.52
UK	271	498	12.86	12.68
Sweden	180	270	0.41	0.50
Denmark	96	85	0.95	1.08

As tabulated in Table 3.2, Germany installed almost 3,900 megawatts (MW) of new PV capacity in 2019. This produced 47.5 terawatt-hours (TWh) of PV-generated energy. Germany has been the top PV installer for several years, with an accumulated PV capacity of 49,016 MW by the end of 2019, ahead of Japan, Italy, and the United States (EurObserv'ER, 2020a). To meet most or all of the country’s energy demand by renewables, approximately 200 GW of PV capacities should be installed by 2050, with an average of 4-5 GW installed annually (Wirth, 2016). This seems like a difficult target but if Germany can power up the whole country with renewables, it can abandon fossil-based fuel and rely fully on clean and sustainable energy.

The consideration of the mass installation of solar PV for this research focuses on the stationary type as it the general type that developers can obtain. Besides solar energy generation, this research also focuses on wind energy.

3.4 Wind Energy

Wind energy, one of the popular renewable technologies is now more reliable and established. Historically, wind turbines (WTs) were used to harness the power of wind for agricultural purposes; to transport water from rivers and canals to fields and farms; to grind grains in mills and for many other mechanical applications. Today, the modern usage of wind power has been electrified. With the advancement of WT operation and utilisation on and offshore, they are now able to produce electricity at a competitive cost as compared to coal and nuclear alternatives. One example that can be observed is the adoption of wind energy as the main source of electricity in Denmark. The installed capacity of wind turbines was 5,917 MW at the end of 2019 contributing to 47% of the country’s electricity. Most of the turbines are installed offshore where the penetration of wind is strongest (EurObserv'ER, 2020b). Table 3.3 shows the level of WT installation in selected European countries.

Wind energy is sought after for its cleanliness and pollution-free promise in the effort to reduce fossil fuel burning for electricity generation. As other consumable energy that wind energy can replace, it can widely conquer the power generation markets, heating and cooling, transport fuels and rural energy demand. Although wind energy generation can be regarded as the most competitive technology in terms of lifecycle cost (Hartmann, et al., 2014), the decreasing price of solar PV these days should be taken into consideration in developing wind energy generation to optimise the benefit of investment.

Table 3.3: Installed WT capacity and generated energy in various countries (EurObserv'ER, 2020b; EurObserv'ER, 2019b).

Country	**Installed capacity (MW)**		**Energy generated by wind turbines (TWh)**	
	2018	**2019**	**2018**	**2019**
UK	1,407	2,178	56.90	63.47
Germany	3,374	2,074	109.95	126.00
Sweden	809	1,684	16.62	19.90
Denmark	657	151	13.90	16.15

3.4.1 Working Principles of Wind Turbine

There are many ways to categorise WT. Two of them are explained briefly in this section.

i. Horizontal vs Vertical

There are two types of WT based on the axial pivoting: horizontal and vertical, meaning the blades of the WT revolve around the axis of the turbine. For horizontal axis wind turbines (HAWTs), usually two or three blades pivoted to the centre point are used. This resembles the look of a fan. Statistics by the UK Department of Energy and Climate Change found that in urban areas in the UK, 84% of the micro/small WT installed are rated less than 1.5 kW. On top of that, of all the WT available, around 97% of them are HAWT (Acosta, et al., 2012).

Schlüter and Ji established that the horizontal type is the dominant one used in existing large-scale wind farms (Schlüter & Ji, 2011). The reason is its self-starting features at low wind speeds. Yet, when fast wind comes from a changing direction, the turbine might have difficulty adjusting itself to face the wind direction. This is a problem that the vertical axis wind turbine (VAWT) will not face as it is independent of wind direction. Besides the mentioned advantages, VAWT also comes with positive acoustic and aesthetic characteristics, highlighted in Mirecki et al. (2007). Regardless of the issues that HAWT might face, the tendency of choosing the horizontal over the vertical type by the designers and manufacturers persists. Figure 3.3 and Figure 3.4 exemplify the common build of the horizontal and vertical axes.

Figure 3.3: HAWT widely used at wind farms (Bloch, 2008).

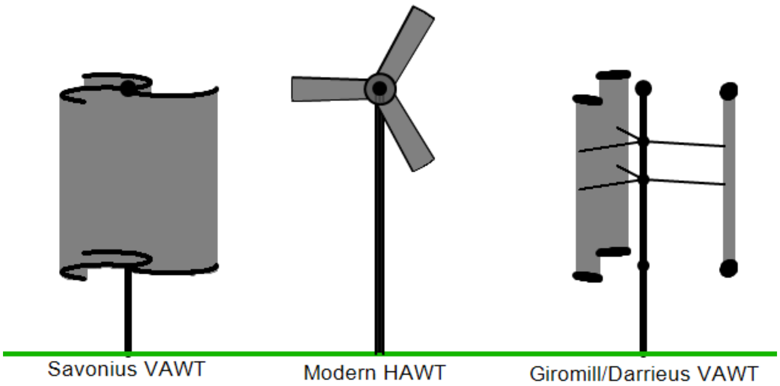


Figure 3.4: Twisted savonius vertical type (left), typical horizontal type (centre) and Giromill/Darrieus vertical type (right) wind turbines. Image from Wikipedia (2017).

ii. Upwind vs Downwind

Besides the axial pivoting of the turbine, another way to categorise WT is by using the wind direction they correspond to, which are upwind and downwind. Some explanations can be found on the US Department of Energy (2017) website. The upwind turbine faces into the wind direction for the blades to rotate, whereas the downwind counterpart faces the opposite. In the case of the upwind turbine, the mechanism works in the way that the wind direction is detected and measured by a wind vane, and it communicates with the yaw drive to position the turbine with respect to the wind. However, no such mechanism is required for the downwind turbine.

Taylor (1983) suggested that downwind turbines can be less expensive as the blades can be coned outwards towards the downwind direction to give sufficient blade-tower allowance. Conversely, variations in output result from this setup. The angle of how the blades is assembled is vital to the amount of energy generated. This involves complex calculations and formula to reach the ideal output. On the other hand, in upwind turbines, the structure of blades could offset the wind load.

This may consume some of the wind energy to start-off the turbine movement, hence lowering the efficiency.

3.4.2 Deployment of Wind Turbines

Wind turbines installed on a tower that houses the hub, rotor and blades do not require much land to be sited. They can co-exist with solar PV and ground source heat pumps on the same land. The footprint of a wind turbine is generally a quarter of an acre (1,011.7 m^2) for the foundation and access roads (Adelaja, et al., 2010). This is the size of the turbine base. If there is more than one turbine placed together at the same site, as studied in this research, it is important to ensure sufficient spacing between turbine towers to avoid wind turbulence and to maximise efficiency.

A study in the US indicates that the modern wind turbine construction commonly has 80-m hub heights. The energy production decreases when the analysis was done using 50-m hub levels (Niblick & Landis, 2016). This is arguably true as wind resources tend to increase with height as observed at high rise buildings. Although wind technology deployment can be seen in many places in developed and developing countries, there are controversial issues regarding WT. Many wind energy facilities have received public opposition regarding noise concerns, aesthetics and safety (Adelaja, et al., 2010). These types of issue could be raised by residents who are not used to modern facilities and technologies around them and might see new installations as harmful to their surroundings. According to research, public awareness through community engagement can provide a better understanding of the installation and that WTs do not pose any hazard (Aitken, et al., 2014). Discussion on WT's potential hazards can be found in Chapter 7.

3.5 Urban Wind Turbine

Wind energy has a great potential to be widely deployed, but some WT models and planning policies make them less effective and not suitable for urban environments (Elliott, 2012). At present, the usage of WT in urban settings is not as widespread as in the open field or offshore and cannot be elevated to be the primary solution to supply the urban energy demand. Utilising brownfield sites with residential blocks and commercial buildings can boost the clean energy production in urban areas. Significant research has been undertaken to explore the options of urban WT and to improve existing designs, especially upon realising its high potential in the urban environment, as noted by Dilimulati, et al. (2018).

Although there are debates against installing WT in or near urban areas due to safety reasons and to minimise visual impacts (Voivontas, et al., 1998), there are many examples of urban WT applications, from micro WTs to large WTs. One significant example of international WT application in the city centre is the incorporation of WT into the bridges connecting the World Trade Centre in Bahrain (Figure 3.5). The large WTs installed in between the towers show that, with careful planning, WTs can easily be integrated into the built environment (Ragheb, 2014). Another example of WT integration into a building is the Strata Tower in London. Although these turbines are said to be static most of the time (Urban75, 2011), if the implementation were successful and did not receive too many objections, some energy would have been generated (Figure 3.5).

As seen in large wind farms and Figure 3.5, the WTs used are of the horizontal type. Most commercial installations are exclusively based on these turbines as they are ideal for open areas with smooth airflow and fewer obstacles. They are also installed high up above ground (Cace, et al., 2007). However, HAWTs are deemed unsuitable for urban installations due to the less intense, but more chaotic and turbulent wind conditions (Kumar, et al., 2018; Beller, 2011; WinEur, 2005).

Figure 3.5: Left: Bahrain World Trade Centre, having three WTs on the bridges (Alzurba, 2008); and right: three WTs installed on top of Strata Tower, London (Urban75, 2011).

The issues of noise, aesthetic, visual (including shadow flickers) and public safety have been a hindrance to an effective deployment of HAWTs in urban areas (Kumar, et al., 2018; Liu & Ho, 2016; Ahmed & Cameron, 2014; Ragheb, 2014). Due to this, VAWTs have been proposed in a few studies as a better choice for cities and isolated semi-urban areas (Kumar, et al., 2018; Khorsand, et al., 2015; Simic, et al., 2013). This is due to the advantages that VAWT offer; including the ability to generate output in low and unstable wind conditions, have simpler design without a yaw system, less vibration, noise and safety concerns, experience less damage and blends in better with the aesthetic of urban landscapes (Kumar, et al., 2018; Tummala, et al., 2016; Pagnini, et al., 2015). On top of that, they also have lower manufacturing and maintenance costs, making them more affordable (Frunzulica, et al., 2016).

3.5.1 Modern Vertical Axis Wind Turbine Applications

One significant disadvantage of HAWT is the aerodynamic efficiency of around 40-55% under steady wind conditions (Tummala, et al., 2016). This can cause a lot of energy wastage, considering that HAWT needs to yaw itself to face the direction of the wind, does not operate well during turbulence and cannot operate under the cut-in and above the cut-off speeds. Another disadvantage of HAWT is the incapability to transform all the wind that comes from a slanted angle when the WT is placed on top of a roof of a building as it works most efficiently when the wind hits the blades perpendicularly (Ragheb, 2014). This is in addition to the inability of HAWT to withstand unsteady wind speeds where most HAWTs rely on steady wind speed for stable power generation and cannot cope with turbulence and gusting wind conditions often found in urban environments (McCamley UK, 2012).

VAWT can be installed in urban areas to overcome many issues related to large HAWTs. With the advantages of VAWT, better energy output can be obtained when the wind potential is amplified by the eaves of buildings, giving an increase of efficiency in the system. This is due to the nature of wind that tends to follow the path with least resistance by going around obstacles (for instance, hills, buildings), resulting in higher wind speed and density around them (Dilimulati, et al., 2018; Frunzulica, et al., 2016; Ragheb, 2014; WinEur, 2005)**.** Ragheb (2014) reported in their study that wind flow deviates long before reaching an obstacle and continues far beyond it. This causes the wind speed and density to increase along with turbulence. If a WT is placed above this turbulence layer, stronger wind speed can be obtained, subsequently transformed into higher energy output.

A VAWT introduced by McCamley and deployed at Keele University in 2012 (Figure 3.6) can cope with turbulence and unsteady wind speeds. It also has a self-starting feature that does not require the turbine to draw energy from the grid to start when the wind speed drops below 2 m/s (McCamley UK, 2012). This self-starting feature is incorporated in most modern WTs as basic, as can be found in various models including Proven WT6000, Iskra, Gazelle, Swift and Quiet Revolution (Cace, et al., 2007). This feature was not common in traditional HAWT that required a starting speed of around 3-4 m/s.

The McCamley VAWT rotate within a stator, which is the stationary part of an electric generator or induction motor that makes them work at a low speed but with a high torque, and are capable of withstanding gusting wind from any direction. The shape almost resembles the H-Darrieus

WTs but their model has extra support on the outer side of the blades causing less vibration and enable it to sustain strong turbulence. When considering significant issues of HAWT like ground vibration and noise, the absence of downforce from the blades results in the reduction of the issues substantially, making the impacts to wildlife a lot less (McCamley UK, 2012).

Besides not having to go through a very tedious and complicated installation process, unlike HAWT, VAWT does not need a tall mast to support the blades and to house the rotor but instead it can be purchased in flat packs, easily assembled and retrofitted onto a roof (Elliott, 2012). This can easily convert roofs of tall buildings in cities to a wind energy harvesting area.

Figure 3.6: McCamley WT with multi-leg design provides extra support for gusting wind in urban environment (Singh, 2012).

Another new design invented to withstand extreme wind speeds can be found in Iceland, a country where a typical wind speed can go up to 40 miles/hour (17.8 m/s). Due to the unique design of this turbine having curved blades with a pointy top, the tough carbon fibre IceWind has several advantages, such as wider wind energy production range (from as low as 2 m/s up to 50 m/s), nearly silent (<35dB), no effect on wildlife and has a 30-year lifetime (IceWind, 2017). There are two types of IceWind: IceWind CW-1000 that can provide domestic power of 1000W at 10m/s, suitable for residential applications and IceWind RW which can be stacked on a mast for increased energy security (IceWind, 2017). Both types of IceWind (Figure 3.7 and Figure 3.8) are considered suitable to be implemented at brownfield sites and buildings categorised as brownfields.

Figure 3.7: IceWind CW, suitable for domestic applications (DiStasio, 2015).

Figure 3.8: IceWind RW, suitable for extra energy security and off-grid usage (IceWind, 2017).

Another WT specifically designed for the urban setting is the Aeroturbine by Aerotecture. With the emphasis on noise and vibration-free features, the ability to utilise the multi-directional and gusting winds with no overspeed protection required, their mono and hybrid turbines are made from low cost and readily available materials (Aerotecture, 2018). Aerotecture's hybrid turbines have solar panel integrated into their turbines, giving consumers continuous RE whenever the system operates (Figure 3.9). This hybrid turbine can be considered as ideal for installation on brownfield sites wherever simultaneous installation of solar PV and WT is allowed, since the harvested energy can complement each other.

Figure 3.9: 712V Hybrid Aeroturbine (Aerotecture, 2018).

As depicted in the previous examples, most of the VAWT and urban WT are either a single-typed Savonius or Darrieus WT. Although Savonius turbines are shown to be an ideal option for urban operations due to their low cut-in speed (Saha, et al., 2008) and Darrieus turbines to be ideal for their low-level noise production (Balduzzi, et al., 2012), both types have better efficiency and self-starting capability due to the drag and lift forces that drive them (Tummala, et al., 2016). Based on an analysis by Ghosh et al. (2015), a combined three-bladed Darrieus-Savonius WT (exemplified in Figure 3.10) demonstrated to yield a higher power coefficient compared to Savonius rotor alone. The hybrid Darrieus-Savonius rotor was concluded as a better solution for the urban usage due to the unpredictable wind condition, better aerodynamic performance and self-starting capability (Tummala, et al., 2016; Frunzulica, et al., 2016; Liu & Xiao, 2015).

Figure 3.10: A combined Darrieus-Savonius VAWT, with Savonius blades closer to the rotor and Darrieus blades on the outer diameter (Types de Energie, n.d.).

In short, the advantages and disadvantages of the HAWT and the VAWT are summarised and compared in Table 3.4.

Table 3.4: Comparison of HAWT and VAWT (Dilimulati, et al., 2018; Vertical Wind, 2013; Cace, et al., 2007; WinEur, 2005)

	HAWT	VAWT
Advantages	1. Efficient in certain conditions 2. Widely used 3. Economic 4. Available from many manufacturers	1. Wind direction immaterial 2. No need for yaw system, simpler design 3. Can benefit from turbulent flows 4. Silent 5. Reliable and robust 6. Less vibration
Disadvantages	1. Cannot withstand changing wind direction well 2. Cannot withstand turbulence or gusting winds	1. Lower efficiency than HAWT 2. Costs more to construct

Table 3.5: Examples of WT products and their suitability.

Product	Type	Suitability
Vestas	HAWT	Large, empty brownfield
McCamley	VAWT	Brownfield with buildings
IceWind CW	VAWT	Urban areas
IceWind RW	VAWT	Brownfield, urban areas
712V Hybrid Aeroturbine	VAWT + solar PV	Brownfield with buildings, urban areas

Different types of WT discussed in this chapter can be compared with a typical large-scale WT, Vestas as shown in Table 3.5. To conclude, some WT including VAWT, can still perform well, but there is still room for improvement to be on par with HAWT for urban applications. This way, more rooftops and brownfields can be converted into green energy harvesting sites. The next section looks at policies related to RE practised in various countries to evaluate and learn best practices to boost RE usage.

3.6 Renewable Energy Policies

There are various policies related to energy developed and implemented, which mainly aim to reduce greenhouse gas emissions, provide security of energy supply and develop efficient and clean energy technologies. Incentives practised to encourage the advancement of RE include the feed-in tariffs (FIT), renewable portfolio standard (RPS), investment tax credit (ITC), production tax credit (PTC), pricing laws, production incentives, investment incentives, international treaties, quota requirements and trading systems (Solangi, et al., 2011).

Feed-in tariffs refer to the regulated minimum guaranteed price per kWh an electricity supplier has to pay a private party for the energy generation fed into the grid using renewable system they own for a period of usually 15 to 20 years (Muhammad Sukki, et al., 2013; Qiang, et al., 2010). Constituting the biggest percentage of initiatives, FIT has been found and recognised as the best and most effective incentive programme ever offered by any government, with half of the world's solar system installation driven by FIT at one point (Kylili & Fokaides, 2015; Park & Eissel, 2010; Pieters & Deltour, 1999).

At the end of 2019, 113 countries had FIT implemented within their policy (REN21, 2020), while back in 2009, only 45 countries utilised FIT to boost their solar PV utilisation (Solangi, et al., 2011). The introduction of FIT sparked an interest to most European countries in terms of solar energy installation, as evidenced by research at Fraunhofer Institute for Systems and Innovation Research published in 2010. The PV deployment throughout Europe was more than 11 GW in 2018 (SolarPower Europe, 2019).

In most cases, different FIT values are used to suit different types of energy and the rated power each system generates. This not only benefits the developer and the owner of the system but also the investors involved. For example, the FIT scheme rolled-out in the UK in April 2010 attracted a lot of new PV installation in the country as the owners of the system benefit financially from the subsidy (Muhammad Sukki, et al., 2013). However, in March 2011, the subsidy was cut by around 50% to prevent it from becoming overwhelmed (DECC, 2011b). The action was taken to reduce the government's liabilities on the national balance sheet, which caused anger to many parties (Mendonça, 2011).

In the end, the government announced for this scheme to be closed by 30 March 2019 (BEIS, 2018). Throughout its implementation, the FIT was a vital instrument to get more involvement from the public in boosting RE installations, as highlighted by Lee et al. (2016). Subsequently, the government implemented a new scheme called the Smart Export Guarantee (SEG) in recognising the need to pay small-scale RE generators for the electricity they export to the grid. The SEG came into force on 1 January 2020 (Energy Saving Trust, 2020). A similar approach was taken in Denmark when their FIT scheme was terminated, however, it was replaced with the green certificates system to encourage the expansion of the RE sector. The certificates are issued to RE producers who can then trade them with anyone willing to purchase at a premium (UN ESCAP, 2012).

Tradeable Green Certificates (TGC) are considered as one of the dominant and most common support schemes implemented in the EU, alongside FIT scheme and competitive auctions (Kylili & Fokaides, 2015; Haas, et al., 2011). It is regarded as a regulatory mechanism that achieves the setting of renewable targets in a cost-efficient way, while eliminating the need for governmental incentives. Electricity generated is sold to the market at usual market prices. Some countries such as Norway, Sweden and Belgium have implemented this scheme as it appears to be a more efficient system providing a consistently higher social welfare than FIT, as evidenced in Tamás et al. (2010).

Another approach in boosting the RE usage is the manipulation of tax whereby reduction or exemption of tax can be imposed by the government to organisations involved in RE developments. This is not limited to the developers and owners but will also encourage and motivate entrepreneurs and investors towards such projects, especially on previously developed land (Bartke, 2013; Solangi, et al., 2011). Research suggests that tax rebates and financial leasing should be offered by banks or financial institutions as part of a government's energy policy, as practised in France and Spain (for example, Lee, et al., (2016), Solangi, et al. (2011)).

The UK Energy Review in 2002 acted as a catalyst towards the increased usage of RE, which implies that policy should be reviewed periodically against the accomplishment that it has achieved. Parallel to this, Rutter et al. (2010, p. 47) posited the same idea describing policy analysis 'as a method to extract findings from each policy in a consistent way to enable synthesis and for quality appraisal for the findings to be interpreted'. The Energy Bill introduced in 2012 and the Climate Change Act 2008 are the major contributors to UK policy (Brown, 2015; Bale, et al., 2012).

In the UK, policies have been implemented to increase the deployment of RE (Lee, et al., 2016; Muhammad Sukki, et al., 2013; Hammond, et al., 2012; Renewable Energy Policy Network for the 21st Century (REN21), 2011; Owen & Ward, 2010). They are formulated by three bodies: central government, local authorities and distribution network operators (DNOs). Central government produces guidelines which are implemented by local authority planners, for example, a guideline to identify suitable sites for RE installations (DCLG, 2015b; 2013), whereas the DNOs are responsible for electricity-related matters, for example, connection to the grid (Palmer, et al., 2019), but what is lacking is brownfield's capability in fulfilling their aims.

Some policies involve financial aids, while some others involve implementation of regulation in buildings and infrastructure. For instance, in 2006 the government announced that all new houses need to be net-zero carbon by 2016 (DCLG, 2006). With a mechanism known as Allowable Solutions, developers could use off-site RE and carbon reduction initiatives to offset carbon emissions, which is not cost-effective to be off-set on-site. Although the initiative was well-intended, unfortunately in July 2015 the effort was stopped due to the significant burden it had put on housebuilders and developers. It consequently made on-site renewables and low carbon infrastructure remain the subject of planning requirements, where local authorities need to formulate different low carbon strategies for different development plans (Energy Technologies Institute, 2016). This directly increased the challenge of building homes (Ares, 2016).

Another way to enforce the utilisation of RE is by obligating energy companies to purchase the power generated by solar PV and supply through their grid connection service. As practised in Germany, the government requires the public utility company to purchase renewable electricity at 65% to 90% of the average electricity price since 1991 and under the German Renewable Act beginning 2000, the payment is guaranteed for fifteen or twenty years (Kylili & Fokaides, 2015). The government also provides allowances to the RE sector, while encouraging distributed generation to improve the supply in regions with no electricity (Solangi, et al., 2011). Such allowances are considered crucial in increasing the competitiveness of solar energy generation.

In the policymaking and planning aspect, potential energies that can be harvested in practical terms is crucial and that calls for the integration of other factors into the analysis (European Environment Agency (EEA), 2009). EEA also suggested local governments to develop medium- and long-term plans of RE utilisation focusing on system operation and maintenance. This is deemed necessary to reduce the cost of power generation for the technology to advance on a larger scale.

Regarding financial support, subsidies can be provided by local authorities or governments to foster innovation and flexibility in RE projects in urban areas (Rydin, et al., 2012). However, they need to be consistent and provide for long-term funding to be able to sustain large-scale projects and prevent an ad-hoc approach of energy generation (Brown, 2015; Bale, et al., 2012; Carley, et al., 2011). Another way of providing financial support is by government-funded banks to attract early-stage developments, while easing the risk of new projects, as recommended by Hopwood (2011).

Authorities or governments have stronger power in overcoming entry barriers to the market than community groups or charities (Hain, et al., 2005).

Policy and regulatory risks represent a major barrier in addition to very limited insurance coverage or alternative risk mitigation in terms of RE investment (Gatzert & Kosub, 2016). Furthermore, diversification is claimed to be one of the most important mitigation techniques with limited insurance coverage. This could lead to low participation and willingness to invest in RE utilisation.

Research shows that the expansion of RE technology in certain places can be hindered by the high price of imported technology from major manufacturing countries (Mundo-Hernández, et al., 2014). For example, good quality WTs produced in Denmark (for instance, Vestas) can be costly for lower income countries. As a result, imported technologies will be a burden if they were to be installed. This issue could be overcome if the equipment is manufactured locally; however, they require an immense investment for research & development (R&D). On top of the excellent policy incentives and reliable technology, funding for R&D in advancing renewable technology and also initiatives in widening grid connection to support private harvesters should be generously considered (Muhammad Sukki, et al., 2013; Solangi, et al., 2011).

Apart from initiating various methods and implementing them into policies, setting clear targets and strategies for RE is crucial. To appear as credible to investors, targets should be linked to specific RE policies to make them meaningful and to ensure their effectiveness (IRENA, 2015). Rather than sticking to one single overarching objective or policy, governments are increasingly adopting RE targets to achieve multiple objectives simultaneously. These vary from energy security, environmental sustainability, to social and economic benefits. Targets can contribute to various stages of the policy-making process, which include formulation, implementation, monitoring and evaluation. They also help in making informed investment decisions and developing a clear vision. Three benefits of setting RE targets are (IRENA, 2015):

a. Serving as guidance during the policy formulation stage, they can provide consistency and enhance the process by offering a common information base to all stakeholders;
b. Signalling political commitment and indicate long-term investment and innovation trends throughout the implementation stage, which effectively improve organisations and motivate stakeholders to act;
c. A measure of policy effectiveness and a platform for review, adaptation and improvement at the monitoring and evaluation stage.

Making targets mandatory is crucial in increasing their credibility and longevity. At the end of 2019, there were 166 countries with renewable power targets (REN21, 2020), with several enacting their targets in law. Having them in law reassures investors that a local market will continue to exist in the future. Moreover, legally binding targets are less affected by political changes as they are harder to repeal (IRENA, 2015). To develop effective targets, research suggests that they should be SMART: Specific, Measurable, Achievable, Realistic and Time-bound (Edvardsson & Hansson, 2005). Besides, they should also be motivational in supporting specific and high-priority policy objectives.

3.7 Summary

RE has played a big role in the efforts of various parties in overcoming climate change. Although various types of RE exist, some countries/cities can only harvest a limited number of RE available to them. To meet the objectives of this research and to utilise available brownfield land in supporting sustainable development, solar and wind-based energy technologies were discussed in this chapter. Furthermore, to advocate the initiative of RE expansion, best practices in policies were discussed. For RE, FIT was concluded as a primary initiative alongside other initiatives such as RPS, ITC, PTC, pricing laws, production incentives, quota requirement and trading systems are offered as an encouragement for RE usage growth (Solangi, et al., 2011).

The following Table 3.6 summarises RE policies practised in various countries. Specific regulations regarding the urban wind turbine installation in the UK is attached in Appendix A for further reference. Chapter 4 continues the literature review with a focus on renewable heat as a type of energy that is transferable and can be reserved. Due to the nature and location of brownfield that is mostly located in developed areas, they can be used to harvest ground heat for various purposes, including to supply for district heating. This type of system is vital in ensuring a more sustainable urbanism.

Table 3.6: Summary of RE policy in selected countries (IEA, 2020a; IEA, 2020b; Lee, 2020; NCSL, 2020; Djunisic, 2019; Sweden.se, 2018; Solangi, et al., 2011).

Country	Major Initiatives Available	Investment Support	Financing Availability	Target Implementation	Legislation	R&D support
UK	RPS, Renewable Obligation, TGC, SEG	Yes	Yes	Yes	Yes (30%, 2020 and 100% by 2050)	Yes
Germany	FIT, tax incentives, electric vehicle tax exemption, energy efficiency initiative	Yes	Yes	Yes	Yes (65% by 2030 and 80% by 2050)	Yes
Sweden	FIT, tax incentive, green vehicle rebate, sustainable car development funding	Yes	Yes	Yes	Yes (54%, 2020 and 100% by 2040)	Yes
Denmark	Green certificates, tax incentives	Yes	Yes	Yes	Yes (33%, 2020 and 100% by 2050)	Yes

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Chapter 4 : Renewable Heat – District Heating and Ground Source Energy Capture

4.1 Introduction

Building on the previous chapters on brownfield regeneration and renewable energy (RE) applications, this chapter continues the literature review on renewable heat (RH). As a complementary component to RE, RH comprises heat that is either recycled or reused. A portion of solar radiation that hits the Earth is stored as heat in the subsurface of the ground and can be captured and reused for heating purposes. This is one type of RH. Such a system can be implemented as an individual heating system or a cumulative system, known as district heating (DH).

To address the objective of this research, this chapter discusses the DH concept and local DH applications in section 4.2.1. Later on, this chapter looks at the heat pumps method of capturing subsurface heat energy. Its applications and the future of ground source heat pumps (GSHP) are also discussed. This method was chosen due to its suitability to be sited together with solar photovoltaic (PV) and wind turbine (WT). The chapter also includes a review of relevant policies relating to renewable/sustainable heat.

4.2 District Heating

The term 'district heating' originated in the 19th century in the United State to describe a system of radiators and using steam condensation to provide heat (Sayegh, et al., 2017). It was then used in Europe in the early 20th century. A core principle of DH is that it uses 'local fuel or heat resources that would otherwise be wasted, to satisfy heating demands by using a heat distribution network of pipes as a local market place' (Werner, 2017, p. 420). As a simpler definition, DH is a heat supply process to large-scale customers in residential or commercial buildings, which is hot water at a certain temperature used for space heating and hot water. This idea of centralised heating can provide low carbon energy cheaply (Sayegh, et al., 2017).

DH systems exist in various schemes and stages across Europe, with a higher concentration of usage in Northern, Central and Eastern Europe, with Poland and Germany leading the market. Scandinavian countries, for example Sweden, have a DH supply of up to 91% of all the energy used to heat space and hot water (Euroheat & Power, 2019; Lidberg, et al., 2017). DH is seen as a way of increasing the efficiency of heat usage when compared to individual property boilers. In Europe, about 6,000 DH networks are operating with a total length of 200,000 km (Connolly, et al., 2014).

Traditional heating systems using coal or oil are the biggest emitters of polluting gases such as nitrogen oxide and carbon dioxide and PM2.5 (particulate matter that has a diameter of less than 2.5 micrometres). The adoption of DH systems in place of these traditional systems can help reduce air pollution from GHG emissions, stratospheric ozone depletion and acid precipitation and therefore help to slow climate change. The system is preferred in many developed countries due to its advantages; they are (Lake, et al., 2017; Sayegh, et al., 2017; Paiho & Reda, 2016; Pantaleo, et al., 2014; Weber, et al., 2007):

1. Comfort for consumers;
2. Decrement of carbon dioxide emission;
3. A mixture of RE sources can be used;
4. Cheapest option in low-density areas;
5. Opportunity to use renewable heat resources;
6. Centralised heat production outside urban areas;
7. Higher efficiency compared to individual heating (and cooling);
8. Environmentally beneficial and financially reasonable when limited retrofit is required.

Largely-connected DH systems can suffer heat loss in transmission and distribution pipes. Guest et al. (2011) addressed this problem in their study of energy loss and increased energy demand on the system. They concluded that loss can be reduced with efficient thermal insulation in larger networks (especially in low-density areas) to ensure the energy demand in the system does not increase unnecessarily (Bartolozzi, et al., 2017; Guest, et al., 2011).

4.2.1 Local District Heating Applications

Over 64% of homes in Denmark are connected to 440 DH networks (Dansk Fjernvarme, 2020), and in Sweden, DH contributes to as much as 91% of all the energy used for space heating and domestic hot water (Euroheat & Power, 2019; Lidberg, et al., 2017). It is also worth noting that their share of RE in DH was close to 70% in 2018 giving Sweden a very low carbon profile (IEA, 2020a). In Sweden, the average distribution temperatures in recent years have been around 86°C in the supply pipe and 47°C in the return pipes. These temperatures are higher than the expected temperatures due to the malfunctioning of substations and client heating systems when the desired temperature is supposed to have a 50°C difference (Werner, 2017).

Old DH systems that run on high temperate networks to connect between large buildings tend to have a high heat loss of up to 30% of the total distributed heat (Gong & Werner, 2015). However, modern DH systems such as those used in Denmark and Sweden, the heat loss is reduced to 20% and

15% of the annual supply, respectively (Elmegaard, et al., 2016; Yan, et al., 2011). This demonstrates a rather efficient DH system.

In the UK, thermal power generation efficiency is between 35-50% for various thermal sources (DUKES, 2017), which accounts for 24% of the national carbon footprint (Bioregional, 2015). But with the low heat utilised, the energy efficiency can exceed 80% (Kelly & Pollitt, 2010). In its moderate climate, 50% of the total energy consumption comes from space heating (DECC, 2012). However, in the UK, DH is still in an early phase, with 210,000 households connected to it, predominantly in new housing developments. There is a new plan to use waste heat from tube stations in London (The Green Age, 2017). Still, there is the difficulty of retrofitting existing buildings.

Some government policies are promoting DH by implementing it in new housing developments and placing the heat generation sites near power plants. For example, in Bicester, Cherwell District Council investigated the potential of collecting energy from a nearby waste plant to heat houses (Wood, 2015). Nevertheless, the mixed experience of DH in the UK showed that some of the existing networks are performing poorly, are inefficient and expensive (Bioregional, 2015).

DH systems can employ different energy sources at once, creating hybrid systems. This gives a technological benefit in terms of the increment of RE usage, higher energy efficiency and greater fuel savings whilst minimising environmental impact (Sayegh, et al., 2017; Mancarella, 2014; Powell, et al., 2014; Manfren, et al., 2011; Chicco & Mancarella, 2009). Parallel to the objective of this thesis, DH is an ideal concept for renewable heat deployment.

4.3 Ground Source Heat Pumps

Ground source heat pumps (GSHP) are used widely in residential buildings and large public buildings for domestic heating and cooling. GSHP has been widely used in Sweden, Germany, Switzerland and North America for decades (Dehghan, 2018; GSHP Association, n.d.). It is one of the promising solutions for heating, ventilating and conditioning (HVAC) to reduce energy consumption in buildings (De Carli, et al., 2014) as well as providing hot water (Dehghan, 2018). These systems are independent of fuel price fluctuations and provide a more secure energy supply throughout the year.

Geothermal or ground energy is said to be one of the most efficient forms of RE in the world. It is clean, sustainable and continuously available (Dehghan, 2018; Arat & Arslan, 2017; Lake, et al., 2017; Atam & Helsen, 2016 (a); 2016 (b)). There are various ways that geothermal energy is used, such as DH, power generation and greenhouse heating (Arat & Arslan, 2017; Arslan, 2008; Satman, et al., 2007; Barbier, 2002). To complement the DH system in this research, the ground can be used throughout the year, as a heat source in winter and possibly as a heat sink in the summer as suggested by Sayegh, et al. (2017).

Even though the Earth's geothermal resources are more than sufficient to supply all human energy needs, only a small portion of it may be successfully harvested (Dehghan, 2018). The operation of GSHP provides a clean way to regulate building temperature, free from carbon emissions. The solar thermal energy that is stored in the ground can be utilised efficiently with the aid of GSHP.

4.3.1 GSHP Application

Installation of GSHP can be made anywhere (Muñoz, et al., 2015), using trenches, boreholes, ponds, lakes or the sea. The main components of a GSHP system are (GSHP Association, 2007):

1. Collector pipe;
2. Compressor;
3. Pump unit;
4. Heat exchanger;
5. Condenser;
6. Distribution unit.

Ground heat is usually extracted using heat collecting pipes in a closed loop. The collector pipes are usually filled with grout for protection and refilled with soil (Dehghan, 2018; Molavi & McDaniel, 2016; Kharseh, et al., 2015; Banks, 2008). The pipes contain pressured water and antifreeze (Centre for Sustainable Energy, 2013; Omer, 2008; Florides & Kalogirou, 2007), which flow to absorb heat in the ground. Once heat is absorbed by the flowing water, it is then transferred onto a separate body of water that circulates around the central heating system. The cooled water that was passed through the heat exchanger is then pumped back to the collector pipe for the next cycle of heat harvesting. The system is illustrated in Figure 4.1.

The most vital part of the system is the heat collector pipe. Usually around 100 m in length, it is buried in shallow trenches in either two-way straight lines or loops (Figure 4.2 and Figure 4.3) or in deeper vertical boreholes (Figure 4.4) (Centre for Sustainable Energy, 2013). In boreholes, U-shape pipes are usually used. Among the types of collector pipes available for heat pumps, the spiral or slinky type (Figure 4.3) buried in trenches is claimed to perform better due to its higher efficiency and lower cost (Zhao, et al., 2016).

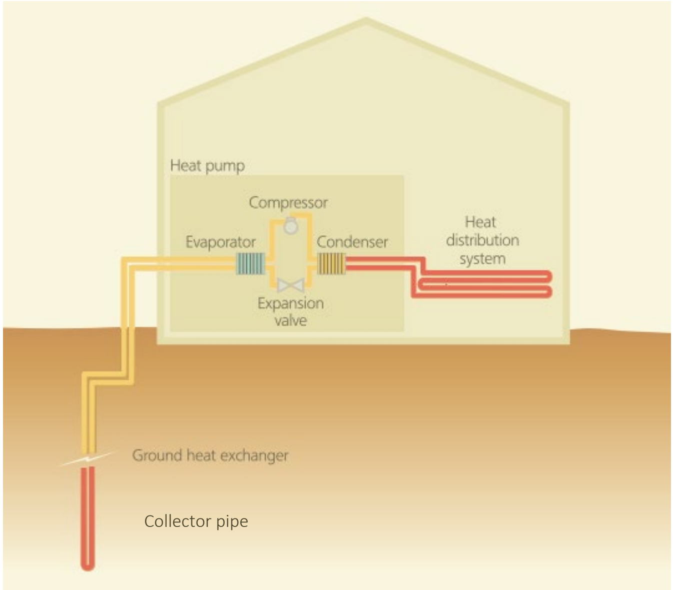


Figure 4.1: Parts of the GSHP system (GSHP Association, 2007).

Figure 4.2: Horizontal loop ground collector (Mesh, 2017).

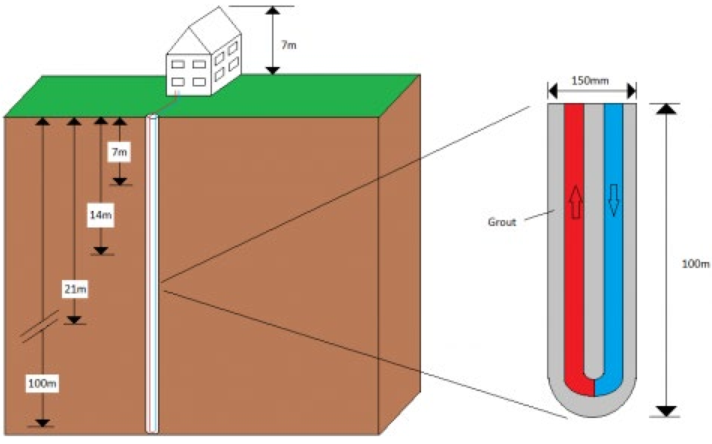


Figure 4.3: Borehole type of GSHP (Cernunnos, 2018).

Figure 4.4: Horizontal slinky coil (GSHP Association, 2007)

The performance of a GSHP system is measured as a coefficient of performance (CoP). It is measured as the proportion of heat output with respect to input in kilowatts (kW). The CoP is largely influenced by both the input and output temperature of the heat source and the distribution system respectively (Muñoz, et al., 2015; GSHP Association, n.d.). For instance, if a heat pump produces 5 kW of heat for every 1 kW of electricity used, its CoP is 5. Other factors influencing the CoP are the correct system size, type of heat distribution system, energy efficiency of the building, current ground temperature and heat demands (Centre for Sustainable Energy, 2013). Despite the difficulty to achieve the maximum CoP stated by manufacturers, the value provided with the system can be used as an indicator (Muñoz, et al., 2015). It is worth noting that the performance of GSHP depends highly on the performance of the ground loop and vice versa, so it is critical to design them together (GSHP Association, 2007).

The compressor in the GSHP system requires electricity to operate and circulate the fluid. By using conventional electricity supply, there will be carbon footprints in the process, but if the electricity is sourced from renewables, the system emits zero carbon to the environment. Bartolozzi et al. (2017) suggested that the performance of GSHP systems can be improved by coupling the thermal generation system with the solar PV and WT systems to meet the electricity demand. This configuration can be applied where solar and wind energies are harvested at the same site as the heat pumps. Solar can be the main supply during the summer and wind turbines can supply for the winter as they are both weather dependent.

Both heating and cooling are possible with GSHP. The system essentially relies on the fact that underneath the surface of the earth, the temperature is constant. This is due to the ability of the ground/soil to store heat from the Sun. Because of the low thermal conductivity of the soil, heat transfers slower than in water and air, causing slow temperature change, resulting in the heat storage ability (Muñoz, et al., 2015; Benli, 2011).

The primary advantage of implementing GSHPs in building heating systems is the significant energy saving and many environmental benefits they offer, compared to using in-house boilers (Liu, et al., 2017; Al-Khoury & Focaccia, 2016; Kharseh, et al., 2015; Muñoz, et al., 2015; Allaerts, et al., 2015; Wang, et al., 2014; Sarbu & Sebarchievici, 2014). Studies carried out to investigate the energy savings GSHP can bring to schools showed that schools with GSHP consumed 26% less energy per square foot compared to the ones without (Shonder, et al., 1996). Other advantages of running GSHP are highlighted in Figure 4.5.

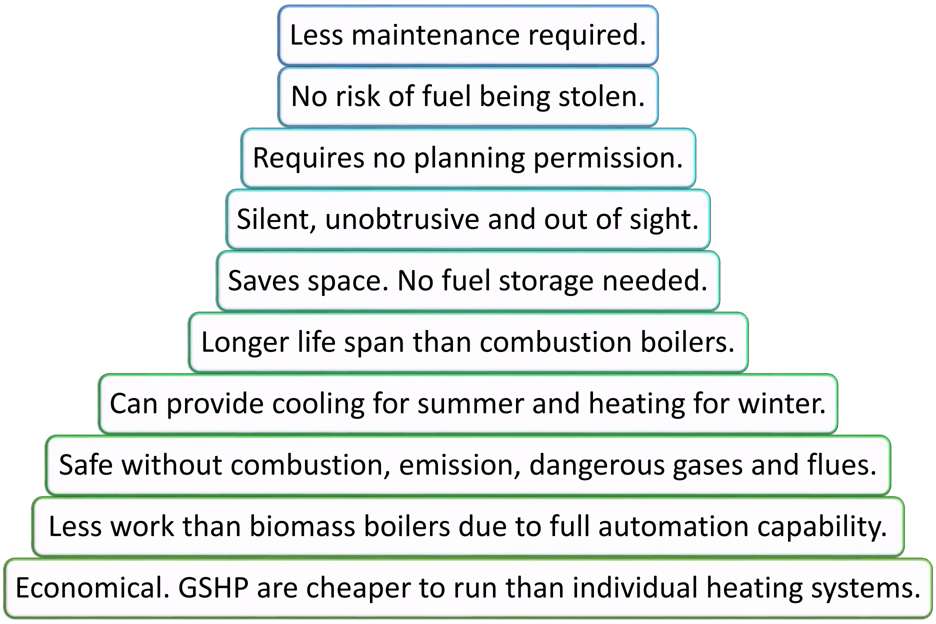


Figure 4.5: Advantages of GSHP (Keçebaş, 2013; GSHP Association, n.d.).

From an economic perspective, GSHPs are costlier to install compared to conventional heating systems. However, the essential maintenance cost is very low. The system can provide safe, reliable and carbon-free heating for over 20 years, making the investment worthwhile (GSHP Association, n.d.). Besides the economy hindering GSHP from being the main source of heat, technical, social and political feasibility also pose a hindrance to a certain extent (De Carli, et al., 2014; Thorsteinsson & Tester, 2010; Hughes, 2008). Lack of awareness of the benefits the system offers, the encouragement to install, policy enforcement and the high cost of GSHP are other hindering factors.

4.3.2 Future of GSHP

GSHPs work best with low-temperature heating systems than conventional wall radiators. As such, they work perfectly well with underfloor heating systems (GSHP Association, n.d.). This, however, does not imply that heat pumps cannot provide for the conventional central heating systems. If the systems are coupled together, radiators with a larger surface area are then required to compensate for the low temperature supplied.

In the event where the GSHP system is not able to supply sufficient energy during peak periods, integrative systems can be used like in hybrid GSHP systems (Yavuzturk & Spitler, 2000; Kavanaugh, 1998). The integration of solar PV to supply the GSHP electricity demands has been recommended by Sayegh et al. (2017) and evaluated by De Carli et al. (2014). Their results show that when the systems are used together, the primary energy usage decreases by about 70-80% compared to traditional systems. Although their assessment was made using PV modules installed on the rooftops of buildings, this can be a guidance for this research, using energy generated at the same site as GSHP.

The redevelopment of brownfield in conjunction with the installation of sustainable heating and cooling has been a pioneering step taken in the Netherlands. Groundwater from brownfield land is treated by means of decontamination and used to regulate the temperature in offices (European Commission, 2013). Donaldson and Lord (2018) and Adelaja et al. (2010) discussed the possibility of directing renewables to brownfield land and using heat pumps to achieve carbon reduction and lowered heating costs. With a lower heating cost, more users would opt for the cleaner technology which in turn saves them money and reduces the environmental problems.

Despite the potential of installing GSHP anywhere, in urban areas, the performance and sustainability of the system might be limited by the spacing of trenches and hydrogeological conditions. The use of horizontal trenches for GSHP would sterilise the possibility for future land use (Younger, 2008). Having brownfield focused for GSHP deployment in this research, technical challenges might arise due to their history of land use and current ground conditions that might be contaminated (Donaldsson & Lord, 2014).

The installation of GSHP highly depends on the geological conditions of the area (Busby, et al., 2009). Horizontal piping is feasible if the site is not rocky and does not need a lot of work apart from excavating. This can reduce the cost of installation. Vertical piping can be an option for borehole systems. Horizontal piping is usually buried in 1-2 m deep trenches (Benli, 2011), whereas boreholes can be as deep as 250 m (Energy Agency, 2018). Elmegaard et al. (2016) recommended for GSHPs to be integrated into a DH system so that future low-temperature heating can be implemented. Heat pumps can form a stable and efficient backbone for DH systems as they can consume electricity from the wind and solar energy generated on-site (Ajah, et al., 2007). In Denmark, GSHPs are often investigated for their ability to utilise wind power to produce 100% renewable systems (Kwon & Østergaard, 2012; Lund & Mathiesen, 2009).

Although Lee et al. (2017) claimed that DH systems usually produce heat and electricity simultaneously, ground-sourced heat can be harvested at the sites where wind turbines and solar panels are installed. Research by Younger (2008) recommended that future work should focus on brownfield utilisation for GSHP to establish the potential energy yield and test economic viability. Paiho & Reda (2016) and Häkämies et al. (2015) recommended to further analyse the system on a large scale after observing its effectiveness in Nordic countries.

Building on previous recommendations, the present research examines the opportunity for GSHPs to be co-sited with solar and wind technologies to consume the renewable electricity generated on-site. This arrangement can yield carbon-free DH systems, as well as allowing brownfield sites to be both renewable energy and heat generators. Two GSHP models are compared in Table 4.1. The heat pumps can provide heat for domestic and commercial uses. Section 4.4 discusses policies practised in the UK, Denmark and Sweden to assess best practices in terms of RH technology implementations.

Table 4.1: Comparison of GSHP models by Kensa with different heat outputs (Kensa Heat Pumps, 2019a; Kensa Heat Pumps, 2019b).

<table>
<tr><th>Model</th><th>Phasing</th><th>Function</th><th>Power</th><th>Heat output</th></tr>
<tr><td rowspan="2">Kensa Commercial Plant Room GSHP</td><td rowspan="2">3-phase</td><td>Heating only</td><td>40 kW, 45 kW, 60 kW and 75 kW</td><td>Up to 55°C</td></tr>
<tr><td>Heating and cooling</td><td>25 kW, 30 kW, 40 kW, 45 kW, 60 kW and 75 kW.</td><td>Up to 55°C and 60°C (for 25kW only)</td></tr>
<tr><td rowspan="2">Kensa Twin Compact GSHP</td><td>Single-phase</td><td>Heating and cooling</td><td>16 kW, 20 kW and 24 kW</td><td>Up to 50°C</td></tr>
<tr><td>3-phase</td><td>Heating and cooling</td><td>20 kW, 24 kW and 30 kW</td><td>Up to 60°C</td></tr>
</table>

4.4 Sustainable Heat-Related Policies

Donaldson & Lord (2018) discussed that to provide a strong low carbon economy for renewable energy and heat, there need to be strategies for the built environment. However, it requires a wide range of renewables, interconnected flows of information, energy affordability and security of energy supply (DECC, 2011a; Scottish Government, 2010). Additionally, policy and decision making processes should be enhanced by employing society motivated energy delivery (Werner, 2017; Batel, et al., 2013).

Energy policies are set to play a significant role in helping to reduce the damage to the environment caused by fossil fuels, as well as limiting greenhouse gas emissions (Wissner, 2014; Thornley, 2012). Deploying DH systems have many advantages, such as thermal power plants with better efficiency, residential dwellings with higher heat efficiency, substitution of oil required for heating and mitigation of climate change (Werner, 2017). Therefore, policy should be formulated to steer towards the DH systems.

A directive set by the European Union in 2010 imposed that greenhouse gas emissions and energy consumption to be reduced by 20% by 2020, while RE resources were to be increased to a level of 20% (Paiho & Reda, 2016; Official Journal of the European Union, 2010). Working towards the same goal, the UK government offers producers of renewable heat a cashback known as the Renewable Heat Incentives to any systems that supply multiple units (Energy Saving Trust, 2020; Donaldsson & Lord, 2014). This applies to those installing GSHP for domestic and non-domestic heating. The incentive acts as a motivation to increase the number of ground source energy harvesters, especially among homeowners.

Due to the carbon dioxide targets set by the UK government, commitments were seen in developing a national heating strategy in the heat and energy-saving sector (Kelly & Pollitt, 2010; DECC, 2009). There has also been a larger reliance on renewables, such as wind and solar technologies to replace fossil fuel usage (DECC, 2014) as a result of the effort to meet the climate change targets as well as devolved regional targets.

In the UK, the existence of private organisations like the Ground Source Heat Pump Association encourages the growth and development of the GSHP industry with their initiatives in a variety of ways (GSHP Association, n.d.):

- Promotion of the efficient and sustainable use of GSHP;
- Raising awareness of the benefits of GSHP;
- Development of installation standards;

- Encouraging high standards of training for the industry;
- Providing a forum for information exchange;
- Lobbying for the ground source energy industry to members of different localisations.

In Sweden, the introduction of landfill bans for combustible waste and organic waste by the government in 2002 and 2005 made waste incineration the final stage of waste management for these two waste types. This created an opportunity for the waste heat generation to supply for their DH. However, in line with the initiative to promote material recycling, the incineration tax was imposed between 2006 and 2010, but that only caused the demand for waste incineration to decrease by a small degree (Werner, 2017; Furtenback, 2009).

The European Energy Efficiency Directive introduced four thresholds to improve the efficiency of DH by which DH systems should pass at least one. They are 50% renewable supply, 50% with excess heat recovery, 75% with cogenerated heat, or 50% of a combination of renewable, excess, and cogenerated heat supply (European Parliament and Council, 2012, Art. 2, def. 41). Research highlighted that the DH system can be a major contributor to the EU's energy objectives (Connolly, et al., 2014) and the change in legislation and regulation to support energy sharing across Europe is a good practice (Euroheat & Power, 2012). While sustaining the energy sharing concept, the regulation relating to pricing of distributed energy needs to be in place to prevent monopoly (Wissner, 2014).

One motivation that can drive the usage of renewable heating is the introduction of carbon dioxide (CO_2) tax, as executed by the Swedish parliament in 1991 under their 'polluter pays' principle. The initiative was inspired by and introduced following the European discussions (Swedish Parliament, 1990, p. 582). This alongside other climate change policies have helped to curb issues relating to climate change in Sweden, whilst becoming the fourth driving force for the DH expansion. As of 2019, the tax level was at 1,180 SEK (around €114/tonne CO_2 emitted) after being gradually increased from the initial level of 250 SEK (around €24/tonne) in 1991 (Government Offices of Sweden, 2019; Werner, 2017). This could be interpreted as a heavy punishment for businesses emitting carbon dioxide in order to enforce their climate change policy and encourage non-fossil-based DH systems.

Although DH has been successful in achieving various targets, public and professional awareness in Sweden was reported to be low (Werner, 2017). The complex nature of the system could have caused this, due to the invisible distribution pipes operating underground. As most of the users were not direct customers and the heat was usually provided to tenants by residence owners, that imposed the lack of awareness on the system used. Renström (2016) discussed ways to increase the demand for DH: 1) to make use of DH in more ways than currently available; 2) increase residents' awareness of the status and give them control over the process of the building's and DH system; and 3) design means for thermal comfort and pleasurable thermal experiences.

In Denmark, the law stipulates for the DH scheme to be non-profit to ensure low prices for customers and good governance. Although sometimes heat generators/suppliers can make a profit, there is a strict control over the matter so customers are not overpaying for waste heat they are using (Bioregional, 2015). Another initiative taken by Denmark is to use their spare wind power to drive electric boilers and heat pumps to achieve their zero-carbon plan by 2025. This is an excellent example of their long-term planning and political consensus that should be adopted by other countries (Ibid.).

A more general finding that can motivate sustainable energy growth is the possibility for the DH cost to be lower than other technologies in the market (Connolly, et al., 2014). To further ease the embeddedness of DH into the society, the installations should be carried out in new developments instead of retrofitting existing infrastructures with a new system (Bioregional, 2015). Additionally, governments should also emphasise on improving energy efficiency in buildings in their planning policy to provide better building insulation and prevent heat loss. With this in effect, it facilitates the adoption of DH systems running on low temperature.

4.5 Summary

This chapter discussed the primary concept of DH and one source of heat supply for the system: ground source heat. Growing from the late 19th century, DH has expanded to become an important household heating system in Europe, particularly in the Nordic countries. Fundamentally offering many environmental advantages, the system also offers great economic advantage to users and generators, as the system can provide heat from various sources. Besides reducing the usage of fossil-based fuels in existing households, free heat from the surroundings can be harvested all year round, without impacting the environment. This includes deep thermal heat from the ground, lakes, sea, and geysers.

The focus of this research has been the shallow thermal energy retrieval from the ground that can be harvested using the ground source heat pumps (GSHP). Consisting of six components, the system can be installed practically anywhere with great flexibility. The system can also be installed at brownfield sites alongside solar PV and WT. This is beneficial as the RE harvested from the solar PV and WT at a particular site can be used to supply electricity for the pumps. GSHP is also advantageous in terms of the design of the heat collector. For installation at smaller places, boreholes can be used instead of trenches, giving it higher energy yield as a result of a deeper subsurface installation. Other advantages of GSHP systems are outlined in Figure 4.5.

To encourage the growth of DH and GSHP utilisations, this chapter discussed some of the policies practised in countries with the systems in place. Energy and heat policies play a vital role in shaping the planning framework to reduce the damage to the environment caused by fossil fuels. The implementation of policies that encourage DH deployment either by retrofitting existing heating systems or installing DH systems in new buildings will boost the need for GSHP. This can provide a better and sustainable heat supply to the society.

In the next chapter, the geographic information system (GIS) models are reviewed, before how the research design and execution is explained, entailing the case study area, the selection of brownfield and RE, environmental analysis and ethical considerations. The model review was vital in determining a suitable model to be used in this research to aid the site identification process.

Chapter 5 : Solar Radiation Models Review for GIS Application

5.1 Introduction

Before addressing the fourth objective of this research to undertake a spatial analysis using GIS, this chapter concentrates on the potential solar radiation models that can be used in GIS software to determine brownfield suitability. This is essential for the implementation of solar technology as it is subject to surrounding areas whereby the local climate and built environment play an important role. Important factors related to solar consideration include atmospheric conditions, agricultural, hydrological and biological processes (Marsh, et al., 2012; McVicar, et al., 2007; Reuter, et al., 2005). It is crucial to understand these processes to comprehend the knowledge of the radiation components used in GIS. Additionally, this knowledge is key in supporting policies of RE (Ruiz-Arias, et al., 2009).

GIS is a comprehensive software package that provides users with tools to analyse and visualise geographic data, utilising extensive functions that allow for transformations to be performed (Shekhar & Chawla, 2003). There are many GIS models suitable for various purposes that produce reliable results. For example, SOLARFLUX, Solar Analyst, r.sun, Solei-32, Kumar's Model and SRAD (Liu, et al., 2012; Wilson & Gallant, 2000) are used to compute solar radiation based on data provided for required parameters.

Due to the extensive availability of the models and the limitation of this thesis, only two models are reviewed in detail in this chapter. They are the r.sun, solar irradiance model developed by Hofierka and Suri (2002), executable in the Geographic Resources Analysis Support System (GRASS), and the Solar Analyst (SA), developed by Fu and Rich (2000), integrated in ESRI's popular ArcGIS, available with the Spatial Analyst licence. These two models are chosen as they are the most widely used tools for solar insolation modelling in the industry and research. Other models apply the same principles as the chosen two, or they yield similar estimates (for example, SOLARFLUX, Solei-32, SRAD), so they are described briefly in this chapter to compare their origins, strengths and weaknesses as compared to the primary reviewed models, r.sun and Solar Analyst.

Most of the solar radiation models are developed based on a digital elevation model (DEM), which uses topographic information to determine features such as elevation, surface orientation and shadow casting. Based on this information, an estimation of the incoming solar radiation at every point of the DEM is made (Ruiz-Arias, et al., 2009). Although the elevation, surface orientation and shadow casts can be derived from the same DEM, they can be treated independently to the use and functions (Rich & Fu, 2000). Different approaches are followed by the models to obtain the estimates. It is noteworthy that using different resolutions will yield different estimations of elevation, slope, aspect and shadowing in complex topographies, despite a similar DEM being used (Ruiz-Arias, et al., 2009; Raaflaub & Collins, 2006).

5.2 Physical Parameters

To understand the basis of the software, it is beneficial to appreciate the physical parameters involved in the back end. The main focus component is the solar radiation, which correlates directly with elevation, slope and aspect; however, a comprehensive solar model combines the effects of orientation, elevation and sky obstruction by surrounding topographies to produce results (Rich & Fu, 2000). Liu, et al. (2012) and Hofierka & Suri (2002) argue that a good solar radiation model should be able to handle arbitrarily oriented surfaces under all sky conditions and take into account four groups of factors which are;

a. sun-earth position: encompasses revolution and rotation;
b. topography: includes elevation, surface aspect, inclination and shading;
c. atmospheric characteristics: gases, water, particles, aerosols;
d. overcast conditions: spatial and temporal cloud.

While the sun-earth position and topography factors can be modelled somewhat accurately using trigonometry, yet, the atmospheric attenuation (attenuation effect during clear sky) can only be modelled by parameterisation[1]. Although less accurate, this method is of considerable merit as the atmospheric composition is relatively stable (Liu, et al., 2012). This is in spite of the challenge faced when accounting clouds, as the observed cloud data cause issues due to rapid changes in weather and cloud conditions. The topography, atmospheric characteristics and overcast conditions are important, as they change the proportion of direct and diffuse radiation of the solar insolation.

The sun's position in the sky is described by the solar altitude and solar azimuth angles. The solar altitude angle is the angular elevation of the sun above the horizon measured from a local horizontal place upward to the centre of the sun (Kumar, et al., 1997). Throughout the year, the changing of the earth's declination angle varies the solar altitude at noon. This causes the noon solar

[1] Parameterisation is the process of finding parametric equations of a curve, a surface, or, more generally, a manifold or a variety, defined by an implicit equation (Hughes-Hallet, et al., 2012).

altitude to vary seasonally. This phenomenon is less obvious nearer the equator, but more so towards the north and south poles. As this research focuses on the location in the northern hemisphere (discussed later in Chapter 6), the solar azimuth angle is the angle measured on a horizontal plane between a line due south and the direction of the site to the sun, as depicted in Figure 5.1 (Ibid). When considering a location in the southern hemisphere, the solar azimuth angle is measured between a line due north instead. Morning values are denoted as positive to indicate the sun going up and afternoon values as negative for the sun going down.

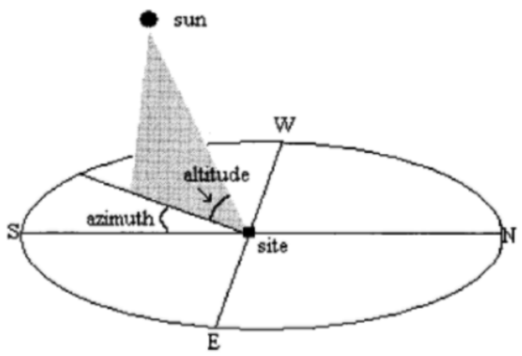


Figure 5.1: Solar altitude and azimuth illustrated for northern hemisphere (Kumar, et al., 1997). In southern hemisphere, a line due north is drawn instead.

Apart from the sun-earth positioning, the topography that describes the surface of the earth or terrain is a significant factor that determines the amount of energy received at any one point on earth (Liang, et al., 2014; Dubayah & Rich, 1995). Variability of elevation, slope, orientation (covers both azimuth and aspect), and shadowing can create a strong change on solar radiation. As a result, soil and air heat up, affecting water balance and primary production, including the synthesis of organic compounds from atmospheric or aqueous carbon dioxide (Dubayah, 1992; Davis, et al., 1992; Brown, 1991; Dubayah, et al., 1989).

5.3 GRASS – The r.sun Model

The r.sun model, developed based on the European Solar Radiation Atlas (ESRA), is utilised in the background of GIS to calculate different components of solar radiation including temporal and spatial variation of albedo (Rigollier, et al., 2000). Although similar models exist, r.sun, with its open-source algorithms is freely available online and has been reported as providing satisfactory results (Agugiaro, et al., 2011; Nguyen & Pearce, 2011; Kyrza, et al., 2010; Hofierka & Kaňuk, 2009).

A comprehensive methodology for spatially and temporally distributed computation for solar radiation is the basis of the r.sun model. It is raster-based software, with spatial input and output data variables (Hofierka & Kaňuk, 2009). Certain parameters need to be put in place when using r.sun, which include the clear-sky index, Linke turbidity factor, time period, hourly step, latitude, longitude, elevation, slope and aspect (Hofierka & Suri, 2002). Linke turbidity factor is defined as the ratio of total optical depth to the Rayleigh optical depth. It is a climatologic parameter that characterises the atmosphere under clear conditions (Ruiz-Arias, et al., 2009).

Within this model, three components are considered when computing the global radiation; the beam/direct radiation, the diffuse radiation and the reflective radiation (illustrated in Figure 5.2). The direct/beam radiation is the radiation from the sun that hits any surface on earth without any blocking or shadowing effect after interacting with particles in the atmosphere (Kumar, et al., 1997). This accounts for most of the radiation in clear sky conditions.

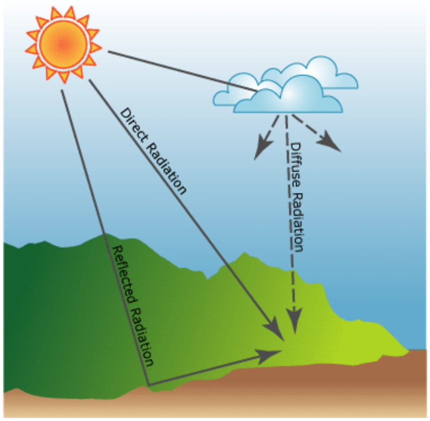


Figure 5.2: Illustration of direct, diffuse and reflected radiation (ESRI, 2016).

Diffuse radiation describes the solar beam scattered out by gases and aerosols in the atmosphere (Fu & Rich, 1999; Kumar, et al., 1997) including dust particles, pollen and sea salt particles, which are considered as the second-largest component of radiation after direct radiation. The reflective component is the amount of radiation reflected from the ground and considered as the least significant (Liang, et al., 2014). Contrarily, Kumar et al. (1997) considered it more important in mountainous areas as there are more reflections from the sloped surfaces in the mountains compared to flat areas. These components are computed for a given day, latitude, surface and atmospheric conditions using built-in parameters with aspect origin 0° at east and increase counter clockwise.

The intensity of extraterrestrial solar radiation is weakened while traversing through the earth's atmosphere. This creates a direct radiation for rays that do not interact with any cloud and a diffuse radiation for rays that hit any surface of the earth after some interaction. Direct radiation is a function of solar zenith angle, solar flux at the top of the atmosphere (also known as exoatmospheric flux), atmospheric transmittance, solar illumination angle on the slope and sky obstruction (Dubayah & Rich, 1995). This means that topographic effects are directly related to the atmospheric conditions. (Direct solar radiation calculation is described in Eq. B.3 in Appendix B.)

Diffuse radiation comes from every direction in the hemispherical sky, described by a function of solar geometry, elevation and the atmospheric scattering and absorbing properties (Dubayah & Rich, 1995). The anisotropy in the diffuse irradiance field and the amount of sky visible from a point, also known as 'sky view factor' (SVF) are considered as contributing factors to the amount of diffuse radiation. As it is anisotropic, the sky direction plays a large role in the variation of diffuse radiation. The scattering component is generally small for most surfaces, except for snow and ice (Ibid) which can vary from 80-90%. Eq. (B-3) and (B-4) in Appendix B demonstrate diffuse radiation computation using Gates' formula.

SVF concerns the visibility of the sky from a given location, taking into account the obstruction of it by topography either by the slope itself (shading) or from adjacent terrain (shadowing) which reduces the diffuse radiation. SVF is defined as the ratio of diffuse sky irradiance on an unobstructed horizontal surface as shown in Eqn. (B-5) and (B-6). Typically, isotropic distribution of diffuse irradiance is assumed as a function of sky direction, which allows for the computation of a single SVF for a given location (Rich, et al., 1994).

Reflected radiation can be estimated by calculating the average of reflected radiation term and adjusting it by a terrain configuration factor, C_t, which include both anisotropy of the radiation and the geometric effects between a certain location and each of the other locations in the topography that are visible. Eq. (B-7) and (B-8) in Appendix B show the estimation of reflected radiation.

In grid-based solar radiation models, direct solar radiation can be computed accurately for flat and inclined surfaces in clear sky conditions with the use of empirical equations to model atmospheric attenuation (Iqbal, 1983) as shown in equation (5-1):

$$I = \begin{cases} I_0\, \tau \cos\theta (SHADE = 0) \\ 0\ (SHADE = 1) \end{cases} \tag{5-1}$$

where I_0 is extra-terrestrial solar radiation, τ is atmosphere transmittance, θ is incidence angle and SHADE is the indicator of the shadiness of the area. Based on this shading algorithm, solar radiation models can be categorised as either solar-based or ground-based (Liu, et al., 2012). For solar-based models, solar altitude in each step of the cell is used in calculating shading. The elevation of each ground point lying on the sun projection line is checked to ensure that it does not obstruct the sunlight. This is the method applied in r.sun (Hofierka & Suri, 2002).

For ground-based models, the observable hemispherical area called 'viewshed' in SA, is outlined first before being calculated. This is the area that the point of interest is exposed to, based on the adjacent terrain where direct and diffuse radiations from this area are not shaded (Rich, et al., 1994; Dozier & Frew, 1990). With the constructed viewshed, a simple check whether the sun is laying within the exposed area is completed instead of iteratively computing at each time step. With the r.sun applying solar-based shading algorithm and SA utilising the hemispheric viewshed algorithm, the former is conceptually simpler than the ground-based computation, which is deemed as more advanced and efficient (Liu, et al., 2012).

The primary difference in terms of the order of calculation iterations between these two categories is that solar-based models are time-oriented, whereas ground-based models are space-oriented (Zhang, et al., 2015). Shading calculation in the models is also a main difference, although slightly different atmospheric attenuation parameters are used in both models. For manual measurements, direct radiation and global radiation can be measured by pyrheliometer and pyranometer respectively.

In mountainous topographies, direct radiation may be significantly modified by shading caused by either the inclination of surface or the blocking of adjacent terrain (Liu, et al., 2012; Fu & Rich, 1999; Kumar, et al., 1997). The shading effect is emphasised as the key factor that may result in the prominent difference of radiation in space and time in complex terrain. Although calculation of shadows caused by inclination can be determined easily using incident angle, shadows that are caused by surrounding terrain can be costly and difficult to compute (Zhang, et al., 2015).

The r.sun model can compute the estimation of the direct, diffuse and reflected components of the clear-sky and real-sky global irradiation for both horizontal and inclined surfaces. Study by Agugiaro et al. (2011) stated that it does not take into account the spatial and temporal variation of clouds as the model uses clear sky conditions only. In contrast, for obstructed conditions, the model accounts for the sky obstruction by computing shadowing effects using digital surface/elevation models (DEM) (Hofierka & Kaňuk, 2009). The proportion of the sky seen from a given point can be calculated by assuming an isotropic sky, to compute diffuse sky irradiance for clear sky conditions. This operation is equivalent to the one of viewshed in SA (Dubayah & Rich, 1995).

The r.sun model works in two modes; instantaneous mode and integration mode (Hofierka & Kaňuk, 2009). In the first mode, the model calculates raster-based maps of solar irradiance and the solar incidence angle, which are measured in W/m^2 and degrees respectively. In the latter mode, integration of the irradiance values is completed for the users' selected time step from sunrise to sunset to produce raster-based maps of daily total solar irradiance and duration of the beam irradiance. These are measured in Wh/m^2 and minutes respectively (Ibid.).

Tests were conducted using the r.sun model and compared against the SA model and real-life observations under clear sky conditions. Then the sensitivity of r.sun was tested using different DEM resolutions ranging from 30 m to 500 m (Liu, et al., 2012). In general, there is a direct correlation between radiation and aspect and elevation, and an inverse correlation between radiation and slope. In the case of grid size, elevation and slope decrease with the increase of grid size (Ibid.). However, due to the resampling process of DEM data and modification of topographic parameters and shading conditions, differences in simulated radiation may occur (Ibid.).

The shading effect is concluded as detectable for a limited area at a fine resolution of 30 m, less than 5% area shading caused a relative difference bigger than 5%. But when grid size increases the shading effect drops below that figure for most areas. On a large scale, the unpredictable values obtained from DEM-based modelling are thus considered as a minor importance (Ibid.). Also, the scale sensitivity test reveals that the shading effect is insignificant except at a very fine scale and a critical threshold scale to be maintained (Ibid.).

Liu et al. (2012) reported that r.sun and SA performed well on horizontal surfaces under clear sky conditions, but show better agreement for inclined surfaces than for horizontal surfaces even though a minor difference was observed. With time-varying parameters, r.sun performed better than SA as SA is more prone to errors especially for equinox and solstice days. It is therefore acceptable to use the agreement of the two models for an inclined surface as verification when data for an inclined surface is not available (Liu, et al., 2012).

r.sun gives slightly higher evaluation for global radiation than the SA model in the valley areas. This may be a result of SA considering microtopography in more detail (Ibid.). For large and high-resolution raster files, calculation of shadows can be completed separately using the r.horizon model (Hofierka, et al., 2007). Horizon maps are pre-computed only once, therefore the r.sun operations can speed up significantly. The r.horizon model repeatedly computes horizon maps for a given area, yielding a specific number of maps for specific directions (Agugiaro, et al., 2011).

Another model developed to improve the applicability of the r.sun model and to handle larger raster files and solar electricity and thermal applications is r.sunyear (Suri, et al., 2007; Huld, et al., 2006). This model estimates the optimal inclination of an equator-oriented plane to maximise irradiation input. Further improvement to r.sun model was made with a combination of vector-voxel 3D solar radiation model called v.sun (Hofierka & Zlocha, 2012). In this model, using a voxel-intersecting rule, 3D vector objects are segmented into smaller polygonal elements. This model has been applied in urban areas to tackle the problem of computing solar irradiation.

5.4 ArcGIS – The Solar Analyst Model

Solar Analyst (SA) or Solar Radiation toolset, is a sophisticated extension model in ArcGIS calculating solar radiation for specific periods. The calculations are executed based on latitude, elevation, slope, aspect, the shadow cast by surrounding topography and atmospheric attenuation. Additionally, shifts of the sun angle to yield global, direct and diffuse radiations are taken into the calculation process (Esri, 2016; Ruiz-Arias, et al., 2009). The total output of solar radiation in SA does not include the reflected radiation; therefore, it is only the sum of the direct and diffuse radiation (Esri, 2016).

The solar radiation tools in SA can perform calculations for specific point locations or entire geographic areas. Four steps are involved in this process (Esri, 2016):

1. The calculation of an upward-looking hemispherical viewshed;
2. Direct radiation estimation based on the overlay of the viewshed and a direct sun map;
3. Diffuse radiation estimation based on the overlay of the viewshed and a diffuse sky map;
4. Generation of insolation map by repeating the process for every location of interest.

5.4.1 Viewshed

SA generates an upward-looking hemispherical viewshed for every location on the DEM to model the shading effects of surrounding areas. This is a key component of the calculation algorithm whereby the generation of a viewshed is completed by generating the view of the entire sky from the ground up using the DEM. The viewshed at a cell is first delineated by searching in a specific set of directions to determine the horizon angles. The amount of visible sky plays an important role in the insolation at a particular location, as it determines the amount of solar radiation that is generated by the software (Esri, 2016). The more visible sky that appears in the viewshed (for instance, an open field), the wider the extent of the sky is down to the horizon and the higher radiation will result as the output of the computation (example in Figure 5.3).

Each cell in the viewshed raster is assigned a value corresponding to the visibility of the sky. The output cell locations correspond to the zenith angle and azimuth angle on the hemisphere of directions (Esri, 2016). Viewsheds are then overlaid with the sun position and sky direction data (represented by a sun map and sky map, respectively) to compute the direct, diffuse, and total (direct + diffuse) radiation for each location and to produce an accurate radiation map (Esri, 2016; Fu & Rich, 2000).

Figure 5.3: Example of a hemispherical image with surrounding trees (Cunningham, n.d.).

5.4.2 Sun Map

A sun map, a raster representation that displays the sun track is created in the same hemispherical projection as viewshed to represent the amount of direct solar radiation originated from each sky direction. The apparent position of the sun is mapped by discrete sky sectors as it moves through the hours of the day and the days of the year (Esri, 2016; Ruiz-Arias, et al., 2009; Fu & Rich, 1999). This is similar to the image of the sun's position moving across the sky over a period of time.

The sun's position is computed based on the latitude of a study area and the time configuration set to define the sun map sectors, which are identified with a unique value, together with its centroid zenith and azimuth angle. The viewshed is then overlaid onto the sun map to calculate the direct radiation once the solar radiation originating from each sun map sector is computed.

For each sun map sector that is not completely obstructed, solar radiation is calculated based on gap fraction, sun position, atmospheric attenuation, and ground receiving surface orientation of the intercepting surface. SA implements a simple transmission model (Fu & Rich, 1999), which starts with the solar constant and accounts for atmospheric effects based on transmittivity[2] and air mass depth.

In SA, the direct insolation from the sun map sector ($\boldsymbol{Dir_{\theta,\alpha}}$) with a centroid at zenith angle (θ) and azimuth angle (α) can be calculated using the equation (5-2):

$$Dir_{\theta,\alpha} = S_{Const} * \beta m(\theta) * (SunDur_{\theta,\alpha}) * (SunGap_{\theta,\alpha}) * cos(AngIn_{\theta,\alpha}) \quad (5\text{-}2)$$

[2] Transmittivity = the transmittance of unit thickness of a substance, neglecting any scattering effects (Dictionary.com, 2020).

where $\boldsymbol{S_{Const}}$ is the solar flux outside the atmosphere at the mean earth-sun distance, known as solar constant. The solar constant used in SA is 1367 Watt/m^2, $\boldsymbol{\beta}$ is the transmissivity[3] of the atmosphere for the shortest path in the direction of the zenith, ***m(θ)*** is the relative optical path length, measured as a proportion relative to the zenith path length (elaborated in (5-3) below), $\boldsymbol{SunDur_{\theta,\alpha}}$ is the time duration represented by the sky sector. For most sectors, it is equal to the day interval × the hour interval. For partial sectors (near the horizon), the duration is calculated using spherical geometry. $\boldsymbol{SunGap_{\theta,\alpha}}$ is the gap fraction for the sun map sector and $\boldsymbol{AngIn_{\theta,\alpha}}$ is the angle of incidence between the centroid of the sky sector and the axis normal to the surface (explained in (5-4)).

Further to that, the relative optical length, ***m(θ)*** is determined by the solar zenith angle and elevation above sea level. For zenith angles less than 80°, it can be calculated using the following equation (Esri, 2016d):

$$m(\theta) = \frac{EXP(-0.000118 * Elev - 1.638 * 10^{-9} * Elev^2)}{\cos(\theta)} \qquad (5\text{-}3)$$

where ***θ*** is the solar zenith angle and ***Elev*** is the elevation above sea level in meters.

The effect of surface orientation is taken into consideration by multiplying it with the cosine of the angle of incidence. Angle of incidence ($\boldsymbol{AngInSky_{\theta,\alpha}}$) between the intercepting surface and a given sky sector with a centroid at zenith angle and azimuth angle is calculated using the following equation:

$$AngIn_{\theta,\alpha} = \text{acos}(\cos(\theta) * \cos(G_z) + \sin(\theta) * \sin(G_z) * \cos(\alpha - G_a)) \qquad (5\text{-}4)$$

where $\mathbf{G_z}$ is the surface zenith angle, for zenith angles >80°, refraction is important and $\mathbf{G_a}$ is the surface azimuth angle.

Total direct insolation is then computed as the sum of the direct radiation from all sun map sectors by the viewshed. On the same hemispherical coordinate system, day hours are divided into equal time intervals.

[3] Transmissivity = a measure of the ability of a material or medium to transmit electromagnetic energy, as light (Dictionary.com, 2020).

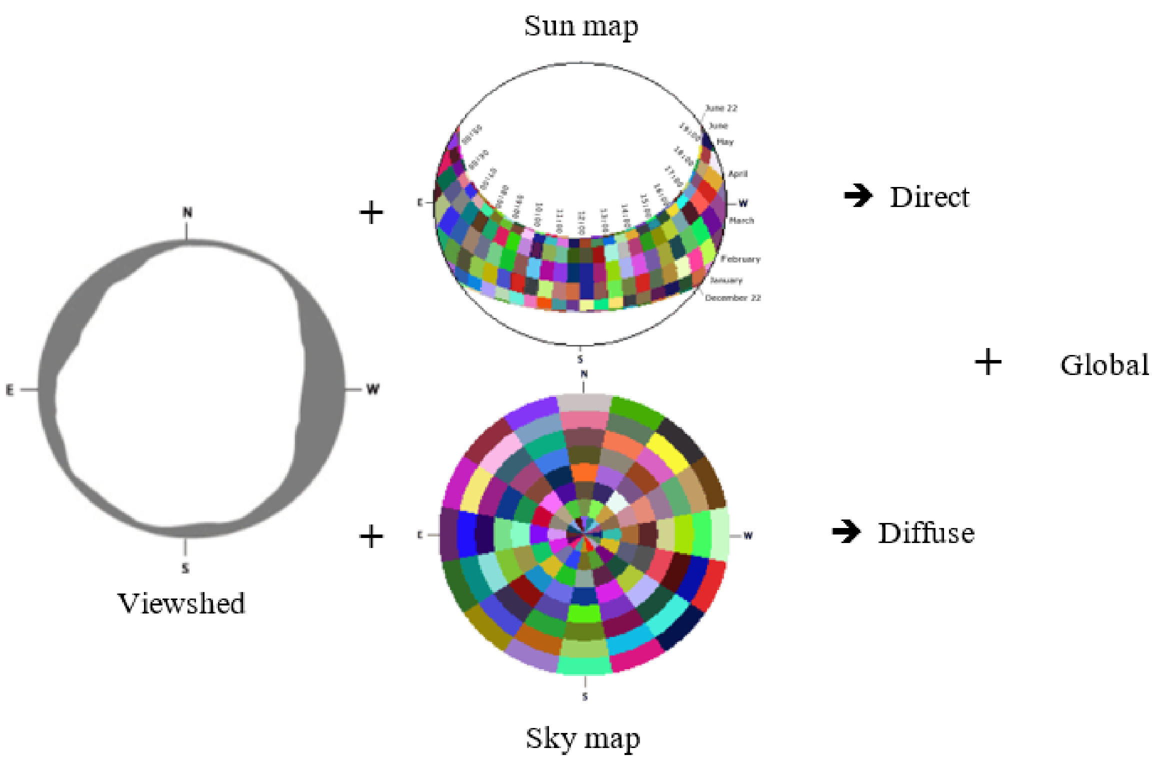


Figure 5.4: The hemispheric vision in viewshed is overlapped with the sun map (direct radiation) and sky map (diffuse radiation) to produce global radiation for a specific time (Tovar-Pescador, et al., 2006; Fu & Rich, 2000). The correct sun direction should be observed according to location of study, e.g. south direction for northern hemisphere vice versa.

5.4.3 Sky Map

The diffuse radiation can originate from any sky direction as a result of scattering in the atmosphere (Figure 5.2). In SA, the whole sky is divided into a series of sky sectors defined by zenith and azimuth angles and represented in a two-dimensional raster map. A unique value is assigned to each of the sectors. The raster map of this is known as 'sky map'.

The sky map is used to generate the diffuse radiation. Similar to direct radiation calculation, the total diffuse radiation is the sum of the diffuse insolation from all sky map sectors (Esri, 2016; Fu & Rich, 2000). Both sun map and sky map use the same hemispherical projection as the viewshed (Figure 5.4). The sun map for direct radiation is obtained by computing the amount of radiation based on a radiative transfer model. Alternatively, the sky map for diffuse radiation is obtained by assuming the diffuse radiation to be isotropic (Tovar-Pescador, et al., 2006). Isotropic model assumes that the intensity of diffuse sky radiation is uniform throughout the sky map, making the radiation incident on a tilted surface, depending on a fraction of the sky map visible to it (Shukla, et al., 2015).

The time between sunrise and sunset is discretised into sun map sectors to yield daily diffuse radiation by summing the diffuse radiation from all of the sectors. For the SVF, the hemispherical sky is discretised into sectors which are the sources of diffuse radiation. The sector's resolution is defined by the number of divisions in azimuth and zenith direction. In this calculation, the horizon angle is key in obtaining the shadowing effect of the surrounding terrain. The SVF is notably more sensitive to the number of zenith division than to the number of azimuths in SA (Li, et al., 2016).

The diffuse radiation (Dif) is then calculated for each sky sector, at its centroid integrated over the time interval, and corrected by the gap fraction and angle of incidence using the following equation (Fu & Rich, 2000):

$$Dif_{\theta,\alpha} = R_{glb} * P_{dif} * Dur * (SkyGap_{\theta,\alpha}) * Weight_{\theta,\alpha} * cos(AngIn_{\theta,\alpha}) \quad (5\text{-}5)$$

where $\boldsymbol{R_{glb}}$ is the global normal radiation, shown in (5-6), $\boldsymbol{P_{dif}}$ is the proportion of diffuse global normal radiation flux. Typical value is approximately 0.2 for very clear sky conditions and 0.7 for very cloudy sky conditions (this can be set by user), $\boldsymbol{Dur}$ is the time interval for analysis, $\boldsymbol{SkyGap_{\theta,\alpha}}$ is the gap fraction (proportion of visible sky) for the sky sector, $\boldsymbol{Weight_{\theta,\alpha}}$ is the proportion of diffuse radiation originating in a given sky sector relative to all sectors (outlined in (5-7)(5-8)), $\boldsymbol{AngIn_{\theta,\alpha}}$ is the angle of incidence between the centroid of the sky sector and the intercepting surface.

To obtain the global normal radiation ($\boldsymbol{R_{glb}}$), the direct radiation from every sector (including obstructed sectors) without correction for the angle of incidence is summed, followed by the correction for the proportion of direct radiation, which equals $\boldsymbol{1-P_{dif}}$:

$$R_{glb} = \frac{S_{Const}\ \Sigma\left(\beta^{m(\theta)}\right)}{1 - P_{dif}} \quad (5\text{-}6)$$

For the uniform sky diffuse model, $\boldsymbol{Weight_{\theta,\alpha}}$ is calculated as:

$$Weight_{\theta,\alpha} = \frac{(cos\theta_2 - cos\theta_1)}{Div_{azi}} \quad (5\text{-}7)$$

where $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_2}$ are the bounding zenith angles of the sky sector, $\boldsymbol{Div_{azi}}$ is the number of azimuthal divisions in the sky map.

For the standard overcast sky model, $\boldsymbol{Weight_{\theta,\alpha}}$ is calculated as:

$$Weight_{\theta,\alpha} = \frac{(2\ cos\theta_2 + cos2\theta_2 - 2\ cos\theta_1 - cos2\theta_1)}{4 * Div_{azi}} \quad (5\text{-}8)$$

Finally, the total diffuse solar radiation for a specific location (Dif_{tot}) is calculated as the sum of the diffuse solar radiation (*Dif*) from all the sky map sectors:

$$Dif_{tot} = \sum Dif_{\theta,\alpha} \quad (5\text{-}9)$$

SA's basic geometrical approach splits the sky into different sectors, defined by their zenith and azimuth coordinate. The atmospheric attenuation is represented by the direct atmospheric transmissivity and the proportion of diffuse radiation according to Ruiz-Arias et al. (2009), whereas Fu & Rich (1999) argue that it is based on the atmospheric transmissivity and air mass depth, as shown in (5-10):

$$\tau = {\tau_s}^{m(\beta)} \quad (5\text{-}10)$$

where $\boldsymbol{\tau_s}$ is the transmissivity of the atmosphere on the shortest path which is the direction of zenith and $\boldsymbol{m(\beta)}$ is the relative optical path length, which is a function of zenith angle and elevation.

Aspect in SA starts at 0° north increasing clockwise. In this model, the shading calculation is employed using the HILLSHADE function. Viewshed is then used to overlay with the sky sectors after being projected and rasterised in order to calculate shadows. Solar radiation in the sky sector is adjusted by the proportion that is not obstructed by the surrounding terrain (Fu & Rich, 1999). However, viewshed delineation and sky size parameters used to combine viewshed and sun map may cause errors in SA (Fu & Rich, 2000; Fu & Rich, 1999; Rich, et al., 1999). The output radiation rasters will always be floating-point type and have a unit of Watt-hours per square meter (WH/m^2) (Esri, 2016).

5.5 Models Compared

Tests conducted by Zhang et al. (2015) demonstrated that SA viewshed is not as smooth as theoretical boundary due to interpolation, with SA underestimating viewshed extent in most directions although viewshed is a key component in calculating the SVF. Overall, SA underestimates viewshed by 8.39%, which results in the underestimation of direct solar radiation throughout the year.

In terms of error, there is no viewshed error when the sun map is located in the middle as that is where the error on viewshed is at its lowest, while large errors can be seen when the sun map is located near viewshed's boundary (Zhang, et al., 2015). Time intervals in SA are represented as discrete sky sectors, which generally assume that small intervals will lead to less error. However, a study conducted by Zhang et al. (2015) did not support this and suggested that SA showed good consistency with theoretical calculation. Zhang et al. (2015) concluded that although SA was less accurate and tougher to understand, it was still beneficial in computing diffuse radiation.

In an experiment run by Li et al. (2016), SA's spatial pattern of seasonal diffuse radiation almost resembled their theoretical calculation, with small spatial variation and relative difference indicated by the standard deviation and range statistics. The difference was caused by the various methods used in computing horizontal diffuse radiation and the large diffuse coefficient used by SA. SA underestimated direct radiation due to numerical integration and its underestimation in viewshed delineation (Zhang, et al., 2015). The model captured the spatial variation of diffuse radiation, but also underestimated it at daily, seasonal and annual timescales. Errors could also be caused by the numerical integration of direct solar radiation (Ibid.). Nevertheless, the SVF modelled by SA also received favourable reports, citing lower errors and said to be a superior model compared to others (Li, et al., 2016).

Another conclusion drawn from an experiment by Ruiz-Arias et al. (2009) stated that SA and to a lower extent r.sun underestimate the daily global radiation, regardless of the resolution of the DEM. In the days with the smallest daily global radiation, SA and r.sun present a slightly smaller scattering. There was also noise introduced in the computed direct transmittance of the atmosphere for the day when there were partly cloudy areas. In general, studies indicate that SA performs better with small resolutions, whereas r.sun provides better results using bigger resolutions of DEM. In terms of sensitivity to the DEM resolution, SA presents the lowest sensitivity that could be the result of the independence of SA towards topography. SA is also concluded as not being able to reproduce the ground data distribution, while r.sun is able to reproduce regardless of the spatial resolution of the DEM (Ruiz-Arias, et al., 2009).

Two approaches can be used for parameterisation. The first is to use observed data to parameterise the state of the atmosphere before the estimate is provided (used in SA). The second is to use the observed data to correct the estimate (used in r.sun). Ruiz-Arias et al. (2009) recommended that the latter approach yields better estimates. Difficulty, however, arises in providing correct values when using the atmospheric transmissivity parameter during the presence of clouds (Ruiz-Arias, et al., 2009). r.sun, on the other hand, models atmosphere attenuation using the Linke turbidity coefficient that has to be obtained for a specific latitude, day and height from a database. Li et al.'s (2016) analysis only included direct and diffuse components of global radiation and abandoned the reflective component from the surrounding terrain as it was considered negligible. Furthermore, there was no effective model to parameterise that radiation component (Li, et al., 2016).

A web-based solar radiation estimation tool, PVGIS was developed using the r.sun model methodology. It can be used to evaluate solar energy for on-site PV installations (Suri, et al., 2007; Suri, et al., 2005) as it includes spatial database and PV estimation feature. The annual PV potential on PVGIS is based on the 1 kWp grid-connected system installed within the existing infrastructure taking into account parameters including geographic location, roof inclination and orientation. In this model, elevation and topographies are represented by a 1000-m DEM.

5.6 Other Solar Radiation Models

SOLARFLUX, a model developed based on the CANOPY model was developed using the Arc Macro Language and implemented in the ArcInfo software. It accepts the topographic surface, latitude, time interval and atmospheric transmissivity information as input to compute total direct and diffuse radiations, duration of direct radiation, SVF, fisheye projections and sky obstructions (Freitas, et al., 2015; Dubayah & Rich, 1995).

The Hillshade function available within the software is also useful to simulate topographic shading (Suri & Hofierka, 2004; Dubayah & Rich, 1995). The SOLARFLUX model is flexible in terms of temporal and spatial spans. Its flexibility allows for modelling the impact of topography on direct and diffuse solar radiation at different scales, including landscape, stand or in a small gap (Bolibok, et al., 2013).

On the negative side, similar to Solar Analyst, SOLARFLUX does not take reflected radiation into account as it is considered negligible. There is not much literature or case studies found on the use of SOLARFLUX in GIS in the recent years. The information on SOLARFLUX is rather limited, and only a few journal articles and papers can be found. This is due to the more recent development and implementation of SOLARFLUX as Solar Analyst, which is available in ArcGIS with the Spatial Analyst licence (Bolibok, et al., 2013). As a result, SOLARFLUX is now obsolete and succeeded by Solar Analyst.

Another solar radiation model, the SRAD model, developed by Wilson and Grant (2000) computes direct and diffuse horizontal and assumes an isotropic portion of the diffuse radiation, monthly average cloudiness and SVF (Wilson & Gallant, 2000). The initial SRAD model was developed to be run on a UNIX platform, and later developed for Windows (Freitas, et al., 2015). Each pixel of an image computed takes latitude, slope, aspect, ground albedo, topographic shading and vegetation classification as its inputs (Ruiz-Arias, et al., 2009). These will provide SRAD the ability to compute shortwave and longwave solar radiations, net irradiance, surface temperature and air temperature (Ibid.).

In SRAD, two approaches are available for direct and diffuse horizontal radiation computation for clear-sky conditions; lumped transmittance and individual transmittance components (Freitas, et al., 2015; Ruiz-Arias, et al., 2009). The lumped transmittance approach is similar to the approach applied in other models, which are Solar Analyst and r.sun where it assumes the attenuation of the direct solar beam in passing through a homogeneous, cloudless atmosphere (Ruiz-Arias, et al., 2009; Wilson & Gallant, 2000).

To calculate the diffuse radiation, a correction is applied utilising circumsolar coefficient. It is defined as the fraction of diffuse radiation derived from within 5° of a direct solar beam (Ruiz-Arias, et al., 2009; Wilson & Gallant, 2000). The estimates for clear-sky conditions are based on atmospheric transmittance, similar to Solar Analyst (Ruiz-Arias, et al., 2009). Moreover, for cloudy conditions, this model has a cloudiness parameter that represents the ratio of actual radiation to clear-sky radiation during cloudy periods, on an average monthly basis (Wilson & Gallant, 2000). Although claimed to be seldom available (Ruiz-Arias, et al., 2009), it can be estimated by considering the monthly average sunshine fraction, the actual monthly average irradiation and the monthly average clear-sky irradiation.

According to a test by Ruiz-Arias, et al. (2009), the SRAD model is similar to Solar Analyst in a way that it uses the observed data from the stations to parameterise the state of atmosphere before an estimate is provided, as opposed to using the observed data to correct the estimate. One weakness of this model is that it requires a parameter file for the computation to be performed, and a file specifying vegetation type at every grid cell.

Monthly average of certain parameters, such as sunshine fraction and cloudiness from weather stations are used to adjust the estimates previously obtained using the model (Ruiz-Arias, et al., 2009). And the longer the climatology used for the parameters, the better the estimations will be. However, it is hard to get a long enough climatology, making it a weakness of this model.

In an experiment by Ruiz-Arias, et al. (2009) their results show a large scattering of estimates for solar radiation. For clear sky conditions, the model underestimates the values, whereas, for overcast skies, it overestimates the values, resulting in the large scattering for various clearness index. The inconsistent results produced a large mean bias error (MBE) and root mean square error (RMSE) for days with clearness index <0.3. The overestimation of values could be caused by the small value of solar radiation under overcast conditions (Ruiz-Arias, et al., 2009).

Solei-32, another software-based solar radiation model was first developed on a DOS environment, which was then implemented in IDRISI GIS. It uses the FORTRAN language to calculate the potential oncoming energy to slopes with different orientations, daily solar radiation, insolation duration, sunrise time, cloudiness albedo and shadow (ref). To compute the mentioned data, Solei-32 takes DEM as input, with other optional data such as vegetation and cloudiness (Mészároš & Miklánek, 2006).

Similar to r.sun, Solei-32 uses the Linke turbidity coefficient to produce estimates for clear-sky conditions instead of estimating the direct atmospheric and diffuse proportion (Ruiz-Arias, et al., 2009). Observed data from weather stations are then used to correct the estimates by the software. This adjustment is important for cloudy days but almost negligible for clear days. For areas with complex topography, it will be a challenge to find a station that is representative of the whole study area to get data that can be used to correct the estimates.

5.7 Summary

This chapter reviewed two of the available GIS models applicable in different software to compute solar radiation. There is a direct correlation between radiation, aspect and elevation, and inverse correlation between radiation and slope. Additionally, the positioning of the sun and earth, the topography at the location, the atmospheric characteristics and the overcast conditions are the major physical parameters that give a significant contribution to the estimation (Liang, et al., 2014; Dubayah & Rich, 1995). Based on the review, models differ in performance when computing different types of radiation due to the diverse approaches applied.

The strengths and weaknesses of r.sun, SA, SOLARFLUX, SRAD and Solei-32 are compiled in Table 5.1 (Freitas, et al., 2015; Bolibok, et al., 2013; Ruiz-Arias, et al., 2009; Mészároš & Miklánek, 2006; Wilson & Gallant, 2000):

Table 5.1: Comparison of solar radiation models.

	Strengths	Weaknesses
SOLARFLUX	❖Topographic GIS capabilities, deliver total direct and diffuse radiation, direct sun duration, SVF, fisheye projections and sky obstructions ❖Hillshade function can be used to simulate topographic shading and integration with the program CANOPY ❖Flexible temporal and spatial spans ❖Meant to be highly flexible and allows for modelling the impact of topography on direct and diffuse solar radiation in various scales: landscape, stand, or small gap in a stand	❖Reflected radiation is not estimated ❖Not many recent literature and case studies can be found, only limited info available including manual ❖Obsolete, developed and implemented as Solar Analyst
Solei-32	❖Calculates potential oncoming energy to slopes with different orientations, daily solar irradiation, insolation duration, sunrise time, cloudiness albedo and shadow ❖Takes DEM as input, with optional vegetation, cloudiness and other input parameters ❖Uses Linke turbidity coefficient for clear-sky conditions instead of direct atmospheric and diffuse proportion	❖Needs a subsequent adjustment using observed data to account for cloud attenuation and correct estimates, similar to r.sun ❖For clear sky conditions, the model overestimates the observed values ❖It is difficult to find a station representative of the whole study area, especially for areas with complex topography

Table 5.1 (continued).

	Strengths	Weaknesses
SRAD	❖Calculates circumsolar radiation derived from within 5 degrees of a direct solar beam to represent diffuse radiation and an isotropic portion of the diffuse component, monthly average cloudiness and sky view factor ❖Computes short- and long-wave radiations, net irradiance, surface and air temperature from inputs such as latitude, surface slope, aspect ❖Direct and diffuse horizontal for clear sky conditions can be computed using two approaches: lumped transmittance and individual transmittance ❖Estimates for clear-sky conditions based on atmospheric transmittance ❖Has a cloudiness parameter that represents the ratio of actual radiation to clear-sky during cloudy periods on an average monthly basis	❖Lumped transmittance is similar to other models, which are Solar Analyst, r.sun ❖Requires a parameter file and a file specifying vegetation type at every grid cell ❖Results in Ruiz-Arias et al. (2009) show a large scattering of estimates ❖Overestimates the observed values and presents the largest MBE and RMSE for days with clearness index <0.3 ❖Noticeable overestimation under overcast skies and fair underestimation under clear conditions ❖Similar to r.sun, the estimates are adjusted using a monthly average of certain parameters, for example, sunshine fraction, cloudiness. The longer the climatology, the better the estimations. ❖It is difficult to dispose of a long enough climatology, making this the disadvantage of this model

Table 5.1 (continued).

	Strengths	**Weaknesses**
Solar Analyst	❖Produces a set of various radiation maps, fisheye equivalent photograph and viewshed ❖Commercial and widely available with ArcGIS, so it is suitable for internal solar radiation computation ❖References are easy to obtain ❖Many case studies of application can be found ❖Estimates for clear-sky conditions based on atmospheric transmittance ❖Flexible in terms of temporal and spatial resolution ❖Performs best with higher resolution, for instance, 20m ❖Uses weather data to parameterise the state of atmosphere before an estimate is provided ❖Does not need Linke turbidity coefficient	❖Underestimates observed daily irradiation, especially for days with clearness index below 0. When the clearness index is between 0.3 and 9.6, underestimating error decreases when daily irradiation increases. ❖Noise can be introduced in the calculated direct transmittance for partly cloudy days ❖Has a low sensitivity to DEM resolution as the diffuse model is independent of topography
r.sun	❖Suitable for calculation over large areas ❖Uses raster maps for terrain, latitude, turbidity, radiation and clear-sky index ❖Optimised for European climate ❖Uses Linke turbidity coefficient for clear-sky conditions, instead of direct atmospheric and diffuse proportion ❖Estimates show a reasonable agreement with observed data, with small underestimation and low scattering (Ruiz-Arias, et al., 2009)	❖Results are good for lower resolution, for instance, 100m ❖Needs a subsequent adjustment using observed data to account for cloud attenuation and correct estimates, similar to r.sun ❖Requires a station to represent the whole study area as data is needed to correct estimates ❖For complex topography, this representation is difficult to achieve

Although the results of estimation by each model are different depending on the input and parameters used, there is a slight deviation in the results. Through experiments, Liu et al. (2012) reported that r.sun and SA performed effectively on horizontal surfaces under clear sky conditions, but show better agreement for inclined surfaces. However, only minor differences were observed. r.sun is believed to provide marginally higher evaluation for global radiation than the SA model in valleys. Using r.sun is beneficial to compute direct solar radiation and SA to compute diffuse radiation (due to the underestimation of direct radiation).

From the review, the differences of r.sun and Solar Analyst established that different models can be useful for different purposes and one model can be better than the other in certain ways. Although SA is said to underestimate the viewshed and the amount of direct solar radiation, the lower value resulting from the formula provides a better output in practice. This is better than overestimating in an early stage but to end up with a lower output after installation.

SA also shows good consistency with theoretical calculation which shows its reliability. Although the theory behind it is tougher to understand (Zhang, et al., 2015), it is advantageous in terms of diffuse radiation computation. Its performance is also better with higher resolutions, giving better accuracy in the results. Furthermore, as the SA model is embedded as a basic function in ArcGIS and has been applied in many cases and studies, it has better support from its developer, Esri and the University due to its commercial subscription. As such, ArcGIS is used for the spatial analysis part of this research with its built-in SA model and a few other functions elaborated later.

In the following chapter, the methods of how this research was developed are set out, before the SA model discussed in this chapter was applied in ArcGIS to obtain part of the crucial data used to identify suitable brownfield sites.

Chapter 6 : Methodology – Multicriteria Decision Making and Analytic Hierarchy Process

6.1 Introduction

Chapters 2, 3 and 4 reviewed the debates in literature regarding brownfield redevelopment, renewable energy (RE), renewable heat (RH) and policies implemented to boost their usage. From the review, issues such as the suitability of brownfield sites and the lack of district heating implementation were identified.

To overcome the issues and achieve the objectives highlighted in Chapter 1, this chapter outlines the method applied to identify feasible brownfield sites for RE and RH siting. It begins with the conceptualisation of this research that emerged from the sustainable city concept and literature review, before it continues with the introduction of the multicriteria decision making (MCDM) method applied alongside geographic information system (GIS). A methodological framework is then introduced, followed by a comparison of five MCDM methods to select the most suitable method for this research.

The selected MCDM method, the Analytic Hierarchy Process (AHP) is applied in Greater Manchester and is elaborated on later in the chapter along with the execution of a workshop. AHP is selected for its straightforward approach, relevance and the various advantages it offers for qualitative evaluation process. Besides the ability to be combined with the GIS spatial analysis, it also provides a high degree of flexibility, reliability and effectiveness through various applications in energy planning, either as stand-alone or integrated with other techniques. Following the discussion of MCDM methods available and the justification of the adoption of AHP, ethical considerations, problems encountered throughout the research and an introduction to Esri's ModelBuilder are later discussed before the chapter concludes.

6.2 Conceptualising Renewable Energy Planning in the Sustainable City

Building upon the literature review in Chapters 1-4, consideration is given to three major relatable components of the United Nations' Sustainable Development Goals (SDG) (Figure 1.1): item 7: affordable and clean energy, item 11: sustainable cities and communities and item 13: climate change. These core items form the basis of this research and can be tackled simultaneously by halting fossil fuel use. As unveiled by the literature, the conventional forms of energy can be replaced with the use of RE such as solar, wind and ground heat.

A key challenge for RE expansion comes from other types of development, especially where there is high demand for land, for instance, housing, public amenities and industries (Martinat, et al., 2018; Loures, et al., 2016; Florea, et al., 2013; Newton, 2013). Furthermore, the demands for land also coincide with the need to meet other sustainable development objectives. As such, this research built upon the utilisation of brownfield as discussed in Chapter 2 to promote land reuse, reduce the competition for land and to curb brownfield increase. This was also to diversify the use of brownfield from the conventional prioritised ways whilst acting as an attempt to achieve the SDG.

Figure 6.1 conceptualises this research by situating the potential energy capture from the surrounding as a key contributor to the SDG. However, the competing demands for land use to meet all the sustainable objectives poses an issue. The research therefore considers the effectiveness of land reuse combined with heat recycling and surrounding energy capture to supply affordable and clean energy to communities, with the aim of identifying the potential of brownfield land to contribute to sustainable city concept that encompasses various aspects of life.

Using parameters set for each technology, GIS models to compute the essential criteria and experts' subjective judgements to weight the criteria, this research focused on the process to identify suitable brownfield sites for solar panel, wind turbine and heat pump siting to harvest RE. As discussed in Chapter 2, the use of brownfield for RE harvesting is still low even in developed countries, giving this research opportunity to address the gap and focus on the RE installation at brownfield sites.

Policy papers reviewed in Chapters 2-4 were considered in the site identification process as preliminary guidance to the spatial analysis. The MCDM method that encompassed the AHP and the application of subjective judgement in energy planning was elaborated in sections 6.3 and 6.4. This produced the key criteria weightings later used in the spatial analysis in Chapter 9. Besides the study of the site identification process as the key output of this research, the execution also enabled the building of a transferable process model, aimed to be applicable in other sustainable energy planning outlined in Chapter 10.

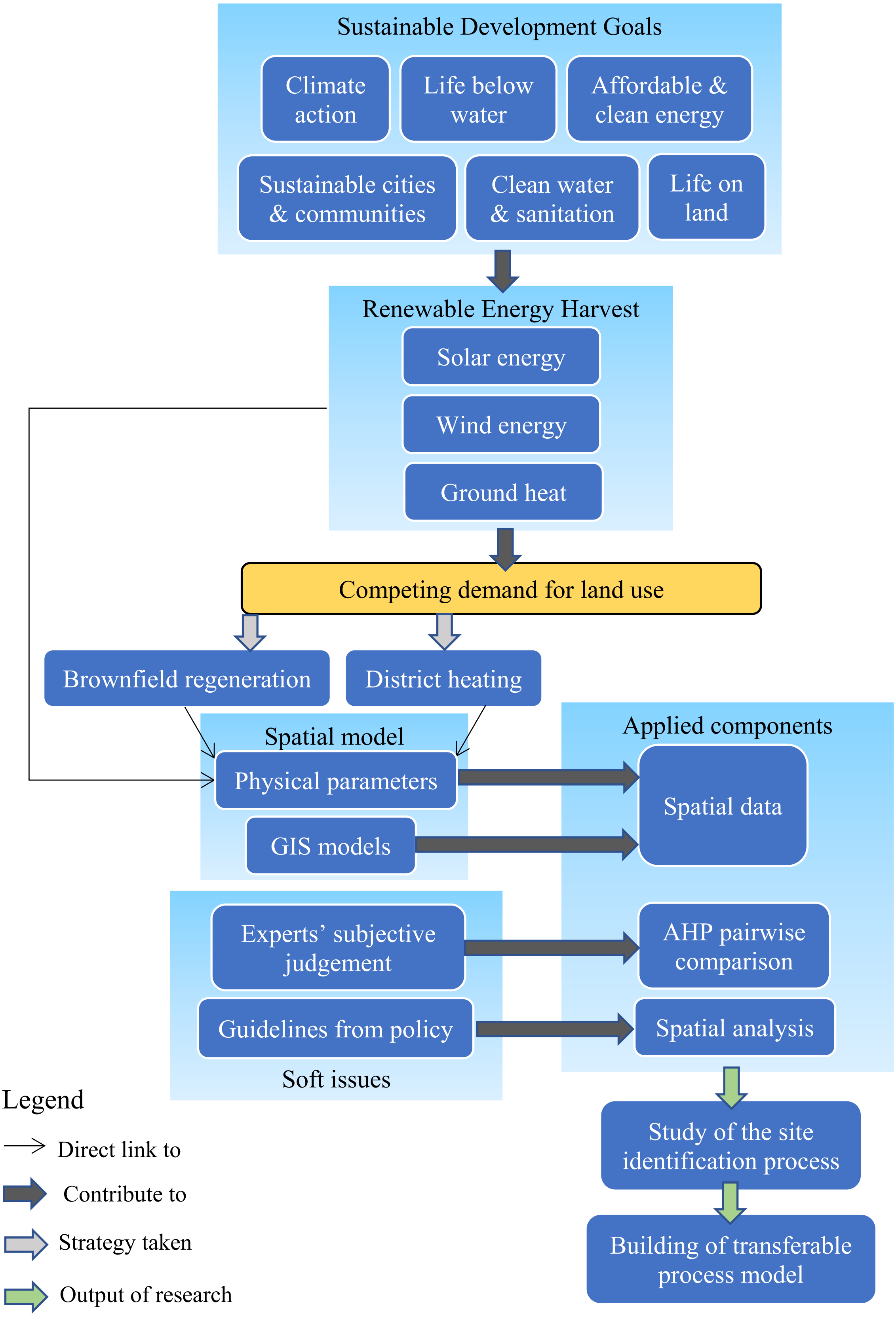


Figure 6.1: Research conceptual framework.

6.3 Multicriteria Decision Making in Sustainable Energy Planning

McCall (2003) emphasised that all types of knowledge are important in decision making. This can be interpreted as objective knowledge related to a certain subject or subjective knowledge that can indirectly be applied to that subject. In making decisions, judgements are usually made using practical reasoning aimed at selecting rational actions, especially when involving problem-solving (Over, 2004). Judgements include decisions about what to do and are closely associated with probability theory, utility theory and statistics (Baron, 2004). One decision making method for complex problems is the MCDM.

MCDM is a branch of operational research to find optimal results in complex scenarios, for example, determining various indicators, examining conflicting objectives and analysing multiple criteria (Kumar, et al., 2017). In energy planning, this method is widely used due to its flexibility when considering criteria to meet pre-defined objectives. MCDM is considered a highly effective evaluation tool to overcome environmental, socio-economic, technical and institutional barriers involved in energy planning (Kumar, et al., 2017; Tsoutsos, et al., 2009).

MCDM can integrate the judgements of a technical expert into policy preferences (Giove, et al., 2009; Linkov, et al., 2007; Figueira, et al., 2005). It also allows the combination of quantitative and qualitative inputs such as cost, benefit, risk and stakeholder views. This is achieved through a systematic approach for integrating uncertainty and technical valuations where trade-offs can be made between competing objectives (Giove, et al., 2009).

Freeman (1984) defined the concept of stakeholder as any individual or group that can affect an organisation's performance or somebody who is affected by the achievement of that organisation's objectives. This definition still stands true in the modern management and project planning area. In the context of project planning and assessment for the public sector, conflicts among stakeholders' decisions are more natural than in an organisation. This is because members of the public do not necessarily share common goals in all aspects, to the same extent as members of an organisation (De Brucker, et al., 2013).

One primary advantage of MCDM is the ability to integrate group decisions for big projects involving many stakeholders and to identify potential area of conflict among stakeholders, which can result in a thorough understanding of values by each of them (Giove, et al., 2009; Linkov, et al., 2006). The group decision made using MCDM should be based on scientific and technical knowledge to bring a relevant solution to any problem. Subjective knowledge and judgement made by different stakeholders regarding alternatives can also aid in achieving an objective consensus in the final decision making process, making it more open and accountable (Higgs, 2006). Applying the MCDM technique creates sustainable development, De Brucker et al. (2013) then regarded MCDM as an ‘institution in action’ due to its ability to create momentum and cause developments to continue.

In this research, MCDM was used to overcome the energy planning issue whilst attempting to diversify the purpose of brownfield redevelopment. To replicate the involvement of members of the public as stakeholders, experts in planning and energy were involved to participate and contribute their knowledge. Expert knowledge was highly valued since it could provide better judgement and influence policy formulation. The decision making process was executed in the form of a workshop considering the advantage of MCDM in facilitating group decision making. It also provided a platform for discussion with experts involved regarding the rating process and the rationales behind their judgements, as well as enabled the researcher to learn more about the technologies.

6.4 Application of Multicriteria Decision Analysis with GIS

To identify suitable locations to site various RE technologies, a set of criteria must be evaluated for their relevance to the RE to be installed. For example, solar radiation is one pertinent criterion for solar farm consideration, but not necessary for siting wind turbines. Some criteria are common for both technologies, for instance, site size. Required criteria for specific technology are elaborated in-depth in Chapter 7. Once relevant criteria are set, their level of importance to the project is assigned before they are used to prioritise brownfield sites.

The multicriteria decision making (MCDM) method was applied to evaluate various conflicting criteria to meet the goal of this research. This method is also broadly known as multicriteria evaluation (MCE) or multicriteria decision analysis (MCDA) and the terms are often used interchangeably. MCDM/MCDA methods provide frameworks for structuring decision problems, designing, evaluating and prioritising alternatives (Demesouka, et al., 2019; Marttunen, et al., 2017; Malczewski, 2006). They differ in terms of objectives and criteria considered and they can either have: (a) one objective and one criterion; (b) one objective and several criteria; or (c) several objectives and several criteria (Carrión, et al., 2008; Jankowski, 1995).

MCDM is particularly suitable to evaluate non-monetary based criteria (for example environmental and climatic factors (Mulliner, et al., 2016). MCDM can also accommodate qualitative and quantitative criteria. Where qualitative criteria may be subjective, different approaches of MCDM can be applied to transform qualitative criteria into quantitative units (ibid). Research in various fields have applied MCDM technique in achieving their goals, for instance, Uyan (2013), Uzoka et al.

(2011), Cavallaro (2010b), Heo et al. (2010), Pohekar & Ramachandran (2004), Haralambopoulos & Polatidis (2003), Beccali et al. (1998).

For this research, the criteria selection and prioritisation were performed using MCDM in conjunction with GIS to combine spatial data and decision maker's preferences over certain criteria, as used in research (Demesouka, et al., 2019; Firozjaei, et al., 2018; Jelokhani-Niaraki & Malczewski, 2015; Malczewski & Rinner, 2015b; Anagnostopoulos & Vavatsikos, 2012). This combination is suggested to be a powerful method in decision making (Ghorbanzadeh, et al., 2018; Feizizadeh, et al., 2017; Khan & Samadder, 2015).

Much research supports the advantages of using MCDM with GIS when selecting sites. Primarily, MCDM is preferred as a decision making tool due to the ability to assess multiple factors and trade-offs by multiple decisionmakers (Thomopoulos & Grant-Muller, 2013; Higgs, 2006). The judgement of weighting factors can be incorporated using their perceived importance, which enables decisionmakers to contribute subjectively (Higgs, 2006). Although the final weightings can be elicited based on initial subjective judgements, the decisions are made with explicit and transparent approach, where scientific equations are employed in the method to transform subjective judgements into objective results (DCLG, 2009). This is said to provide more reliable result than using informal judgement.

In MCDM analyses, objectives and criteria that form part of the components or hierarchy can be further analysed or changed if they are considered to be inappropriate (DCLG, 2009). In doing so, a simple change does not require the whole analysis to be run all over again. MCDM techniques also offer the ability for experts to be involved in decision making due to their advantage of incorporating multiple decisionmakers' judgements (DCLG, 2009). This will avoid bias in decisions made by a sole executor. Using MCDM in a broader context beyond the decision making body and experts allows for it to be a means of communication between decisionmakers and the wider community (DCLG, 2009).

When combined with GIS, MCDM analysis provides a more convenient way of conducting spatial analysis (Higgs, 2006). The GIS toolbox can complement and ease the process where weightings elicited using MCDM can be embedded in the evaluation. Furthermore, a large number of alternatives can be evaluated simultaneously using GIS (Higgs, 2006; Carver & Openshaw, 1992). Using the combination of MCDM with GIS also reduces any costs involved and time taken to run site identification analyses (Higgs, 2006). This can be a major factor for the adoption of MCDM in conjunction with GIS. Sensitivity analyses can also be performed in GIS using modified MCDM results (Ibid.). In particular using ModelBuilder described in section 6.11, sensitivity analyses can be done conveniently by substituting the values of the criteria.

Three steps are involved in solving general multicriteria problems: 1) deciding the type of MCDM; 2) applying the method to the criteria to assign weightings; and 3) standardising the values of criteria to a common scale (Ghorbanzadeh, et al., 2018). Five MCDM methods are compared in this chapter before the selected method for this research is justified. The spatial analysis using GIS was executed with the aid of the adopted MCDM method.

To select a suitable area for this research, a consideration in the following factors were made: an area with a large number of brownfield sites, spatial data available and local authority with an interest to redevelop their brownfield sites. As a result, Greater Manchester (GM) was chosen. The GM brownfields were identified for potential RE harvest. Once the study area was fixed, the selection criteria for specific technology were set, elaborated in Chapter 7. The GIS data for the relevant criteria were obtained from open sources. To complement the GIS analysis, weightings for the criteria used were collected from workshop participants. The workshop and the software used to collate weightings are explained in sections 6.6, 6.7, 6.8, 6.9. Using the relevant criteria and weightings obtained, the site identification process was executed.

All the steps taken in the GIS analysis including the selection criteria incorporated and weightings applied are combined into models built using an ArcGIS's extension, ModelBuilder. This produced easy-to-run files transferable to different projects with different requirements and priorities. They also simplified the process involving iterative analysis. A complete process framework is illustrated in Figure 6.2.

Sections 6.4.1 to 6.4.6 compare different MCDM methods that are applicable for site identification projects, applied in various literary works such as Demesouka, et al. (2019), Firozjaei, et al. (2018), and Jelokhani-Niaraki & Malczewski (2015). The selection of relevant criteria and gathering of respective data are highlighted briefly in section 6.6 and elaborated in greater detail in Chapter 7. The expert recruitment process and workshop flow are discussed in sections 6.8 and 6.9. The criteria weighting, site identification and map production processes are explained in Chapter 8, with the results for Greater Manchester presented in Chapter 9. Upon obtaining initial results using the first set of weightings, different cases were built to explore the effect of different weightings on the final brownfield scores and the site priority map in a sensitivity analysis. The importance of this step was acknowledged by Higgs (2006), noting the options of conducting sensitivity analysis using different weightings or MCDM techniques.

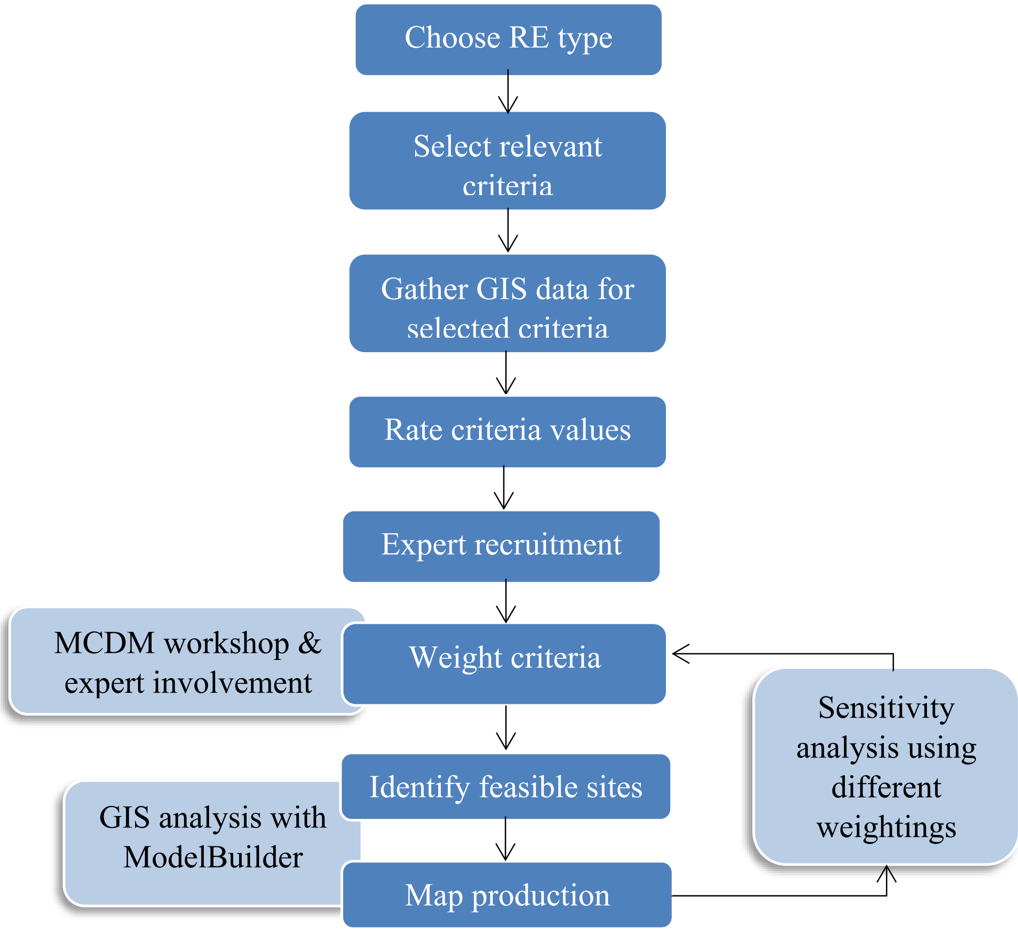


Figure 6.2: Process framework.

6.4.1 Methods within MCDM

Deciding on a specific technique to handle spatial problems is the first and vital step and a different degree of information is required for different MCDM techniques (Demesouka, et al., 2019). MCDM can be categorised into two; continuous and discrete, depending on the nature of criteria/alternatives being considered in the process (Hajkowicz, et al., 2000). Continuous methods include linear programming and aspiration-based models (Uzoka, et al., 2011), whereas discrete methods have a set of objectives, a finite number of alternatives, criteria for evaluating alternatives and a method to rank the alternatives (Ananda & Herath, 2009).

Continuous problems usually consist of a vast or infinite amount of decision alternatives (also known as Multi-Objective Decision Making (MODM)), whereas discrete problems try to give priorities to a set of finite alternatives (Zavadskas, et al., 2014; Hwang & Yoon, 1981). Various methods are available in the discrete category for decision makers to choose from, which are further classified into three types: weighting, ranking and mixed-method.

Discrete MCDM are most suitable in evaluating non-continuous elements with varying degrees of intensity. In this section, continuous and discrete techniques are compiled in Table 6.1, before five discrete techniques are compared to identify and justify the most suitable technique to be applied. They are the Simple Additive Weighting, Fuzzy Technique, TOPSIS, ELECTRE and AHP. A more comprehensive comparison of MCDM categories can be found in Mosadeghi (2013) and DCLG (2009).

As the main need for the MCDM was to complement the spatial analysis using GIS, a suitable method to weight the criteria was selected and without the need to evaluate or rank all the available alternatives/brownfield sites. The MCDM chosen needs to be relatively easy to use and to be understood, so that they can be adopted by non-experts in other planning projects. A method that can aid both quantitative and qualitative analyses would be advantageous.

Table 6.1: Comparison of MCDM methods.

Type of alternatives	Category	Method	Originator/note
Continuous	Linear programming	Linear optimisation	To find the best outcome, such as maximise profit or lowest cost using linear relationships (Schrijver, 1998)
	Aspiration-based models	Decision made based on the level of user aspiration	User adjusts the level of aspiration for each objective while obtaining feedback on their reasonableness (Lotfi, et al., 1992).
		TOPSIS	Hwang & Yoon (1981)

Table 6.1 (continued).

Type of alternatives	Category	Method	Originator/note
Discrete	Weighting	Simple Additive Weighting	Hwang & Yoon (1981)
	Ranking	PROMETHEE	Brans & Vincke (1985), known as outranking method
		Fuzzy	Zadeh (1965)
		OWA	Yager (1988)
	Mixed method	AHP	Saaty (1980)
		ELECTRE	Roux & Elloy (1985)
		MAUT/MAVT	Von Winterfeldt & Edwards (1986)
		Value Focused Thinking (VFT)	Keeney & Evans (1993)

6.4.2 Simple Additive Weighting

The simple additive weighting (SAW) method is the simplest way to combine scores of criteria and their weightings. This method is also known as the weighted sum model, weighted linear combination or weighted linear scoring method, and it works on the principle of weighted average. The method involves adding the score of each alternative multiplied by their respective weighting. In general, SAW deals with benefit criteria, where the highest score is assumed as the best (Mulliner, et al., 2016). The principle assumes that the score/preference of one criterion is independent of another (Chabuk, et al., 2017; DCLG, 2009, p. 22). It is important to note that this method is applicable only when all the data evaluated are expressed in the same unit, for example, all criteria are measured from 0 to 100.

SAW is based on a simple formula to evaluate each alternative, A_i, which is:

$$A_i = max \sum_{j=1}^{n} W_j \times N_{ij} \tag{6-1}$$

where A_i = the suitability index for the region under consideration, i, W_j = relative importance of normalised weight of criterion, N_{ij} = standardised rating value of area i under criterion j, n = number of criteria.

Each alternative score in the SAW method can be computed by multiplying the normalised weight of criteria importance (W_j) with the standardised rating value of sub-criterion (N_{ij}). It needs to be noted that the total weightings for all criteria should be equal to 1 (if the weightings are in decimals). The most preferred alternative is the one with the highest score. This straightforward technique in assigning weightings to criteria is one of SAW's advantages, as the calculation is simple it does not require complex computer programs (Velasques & Hester, 2013).

The weighting and score of each criterion are assigned by the decision maker using their subjective judgement and preference. Hence, it is important to have the criteria independent of each other. When predetermined assessments and weightings are available, SAW can be easily applied to produce the final weightings which indicates the most ideal alternative (Putra & Punggara, 2018). However, according to Velasques & Hester (2013), when many criteria need to be weighted and scored by the decision maker, the judgement can be slightly inconsistent, making the direct scores given not reflect the real situation. This subsequently produce an illogical result.

In research where simulation was done to compare the behaviour of different MCDM methods, SAW was concluded to behave similar to AHP (Zanakis, et al., 1998). This suggests that even when subjective weightings are assigned using different methods, similar results can still be achieved. One disadvantage of the SAW method is that all criteria must be of the same nature, meaning either all cost or all benefit and cannot be used as a combination within the same analysis (Mulliner, et al., 2016). Although the multiplication and summation processes are straight forward, if there is a varied nature of criteria, a transformation process is necessary. This might make the process more complicated and time-consuming for potential users, especially when a large number of criteria is involved.

Although the SAW method provides an easy way to score criteria based on each alternative and subjective weightings, the need for an MCDM method for this research was to determine weightings of criteria for further GIS processing, instead of directly ranking all the alternatives on paper. Thus, the SAW method was considered unsuitable.

6.4.3 Fuzzy Technique

The fuzzy technique was first introduced by Zadeh (1965) as fuzzy set theory, an approach that simulates the complex systems that are difficult to explain by integers. Fuzzy deals with problems that do not have clear boundaries and models common sense reasoning which does not fit well with techniques that involve exact reasoning (Uzoka, et al., 2011; Giarratano & Riley, 2005). It allows for the input to be ambiguous, imprecise or vague (Balezentiene, et al., 2013; Velasques & Hester, 2013) and therefore is able to deal with uncertainty (Carrión, et al., 2008). Fuzzy is also said to be advantageous when dealing with a lack of information in decision making (Latinopoulos & Kechagia, 2015; Velasques & Hester, 2013).

As opposed to the classical logic set where an object either belongs to a particular set or not in a binary manner (1/0, true/false, etc.), fuzzy sets allow an object to be in the range between 0 and 1 as a membership value (Mallick, et al., 2018; Zadeh, 1965). This method can handle vague and imprecise data; it is quite similar to human decision making that can work with approximate reasoning to produce a precise solution explicitly. For instance, instead of expressing a qualitative judgement as 'attractive' which is a definite value of 1, 'fairly attractive' can be used, which is then represented by a certain degree of fuzzy membership, lying between 0 and 1. Using the expression of judgement based on a value between 0 and 1, fuzzy models develop procedures for aggregating weightings that are also represented as fuzzy quantities (DCLG, 2009). Examples of fuzzy techniques include fuzzy weighted sum and ordered weighted averaging (OWA).

A typical fuzzy set is defined as $F = \{(x, \mu_F(x)), x \in \mathbb{U}\}$, where $\mathbb{U}$ is the universe of discourse and μ_F is the membership function such that $x \rightarrow \mu_F(x)$, and $\mu_F(x) \in [0,1]$. The set $\{x: \mu_F(x) > 0\}$ is the support of the fuzzy set F (Lazzerini & Pistolesi, 2015). Fuzzy functions are usually based on shapes to model preferences. One of the commonly used shapes is triangle (Brunelli, 2015). As exemplified in Figure 6.3, the fuzzy function $\tilde{T}$, is given by (Ibid):):

$$\mu_{\tilde{T}}(x) = \begin{cases} 0, & \text{if } x < l \text{ or } x > u \\ \dfrac{x-l}{m-l}, & \text{if } l \leq x \leq m \\ \dfrac{u-x}{u-m}, & \text{if } m \leq x \leq u \end{cases} \quad (6\text{-}2)$$

where $l \leq m \leq u$. Alternatively, $\tilde{T}$ can be represented using alpha-cut or the interval of confidence, which is $T_\alpha = [l^\alpha, u^\alpha] = [(m-l)\alpha + l, -(u-m)\alpha + u], \forall \alpha \in [0,1]$.

A comparison in a study by Uzoka et al. (2011) showed that the fuzzy technique is slightly better than AHP, but without any significant statistical performance; whereas in other research such as Mallick et al. (2018), Asakereh et al. (2017) and Feizizadeh, et al. (2014), they applied the fuzzy technique alongside AHP to yield the final results. It was based on the claim that AHP cannot depict the decision making process for quantitative-based preferences appropriately that the fuzzy combination was evolved (Mallick, et al., 2018).

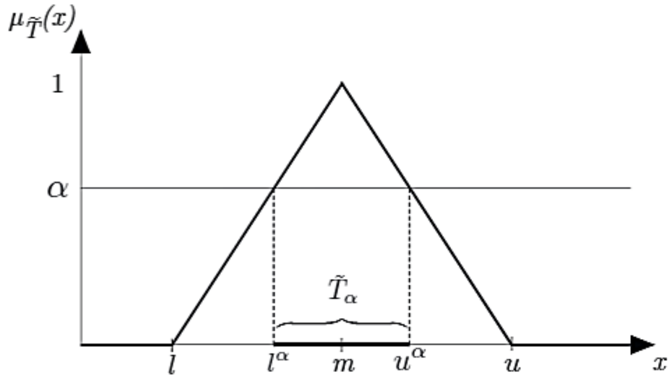


Figure 6.3: A graph showing a triangular fuzzy function (Brunelli, 2015).

Despite the claims that various researches have made regarding the significant increase of performance and accuracy and obtained greater flexibility by using the fuzzy method (for instance Mallick et al. (2018) and Asakereh et al. (2017)), the usage of fuzzy can be substantially complicated in application and difficult to develop (Nefeslioglu, et al., 2013; Velasques & Hester, 2013). This is especially true when decisionmakers are not specialists in the method, as the fuzzy approach does not have clear theoretical foundations from the perspective of modelling decisionmakers' preferences. The imprecision captured by fuzzy and the mathematical operations that can be executed on them are doubted whether they truly match the real fuzziness of human judgement (DCLG, 2009; French, 1988). Furthermore, there are no critical advantages of the method that are not available in other methods (DCLG, 2009).

Apart from the unclear advantages in the model itself, the complexity of the system can increase exponentially with an increase in the number of criteria involved. This is primarily caused by the increased number of membership functions that need to be solved and after a certain complexity, the system may become unsolvable or not executable (Nefeslioglu, et al., 2013). Due to the use of the fuzzy technique that results in a higher uncertainty although applied in various applications and research especially combining the usage of the fuzzy technique with AHP, this combination of methods was discouraged by its originator, T. L. Saaty (Saaty & Tran, 2007). They further argued that valid answers depend on good judgements and fuzzifying these judgements is simply a perturbation that leaves the results where they are without making the outcomes better. The application of AHP alone has been demonstrated to produce valid results if the judge/decision maker is well informed, hence changing the numbers to cope with uncertainty does not change the answers substantially or lead to the actual answer (Ibid).

In an experiment run by Świtalski (2001) to examine the transitivity using the fuzzy technique, they evidenced that intransitivity existed in almost every participating subject, with at least one nontransitive triple when comparing preferences for 10 triples. They further concluded that, although human preferences can be represented by fuzzy relations, when there are many preferences to be assessed, human judgement may violate the transitivity rule. From the review, the fuzzy method requires more understanding of uncertainty and it involves more mathematical calculations. There was also no clear advantage of fuzzifying data for GIS usage in this research. For this reason, the fuzzy technique was deemed unsuitable and was not applied.

6.4.4 TOPSIS

The Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) was developed by Hwang and Yoon in 1981 to rank alternatives. The method works based on identifying solutions that are as close as possible to the ideal solution and as far as possible from the negative ideal solution (Kaliszewski & Podkopaev, 2016; Sánchez-Lozano, et al., 2016; Hwang & Yoon, 1981).

TOPSIS works as a continuous model and through mathematical operations, it considers the weights of each criterion evaluated and whether they are a cost or profit criterion to determine which value is closest to the positive or negative ideal solutions. To evaluate criteria, variables with different units of measurements can be used. There are 7 steps in executing the TOPSIS method and they are described as follows (Jozaghi, et al., 2018):

Step 1: Determination of criteria weightings and construction of decision matrix. Criteria weightings need to be determined by other methods before a matrix can be constructed, such as subjective opinions or objective approaches which involve mathematical calculation. If a subjective approach is applied, a ratio of each weighting to the lowest weighting should be obtained, which can be w_j/w^*, where w^* is the lowest score assigned to the least important criterion and w_j is the score for the jth criterion. The weightings are then normalised by dividing each of them by the total.

Step 2: Calculation of normalised decision matrix to transform various attribute dimensions into non-dimensional units. Standardised equations are used to normalise each attribute x_{ij} in the decision matrix $X = (x_{ij})_{mxn}$ in relation with each alternative, A_i. Eq. (6-3) shows a commonly used equation to calculate the normalised value r_{ij}.

$$R = \left(r_{ij}\right)_{mxn} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{pmatrix} u_1 & u_2 & \cdots & u_n \\ r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} \quad (6\text{-}3)$$

where for benefit attribute:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m}(x_{ij})^2}} \tag{6-4}$$

and for cost attribute:

$$r_{ij} = 1 - \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m}(x_{ij})^2}} \tag{6-5}$$

Step 3: Computation of the weighted normalised decision matrix. The weighted normalised value v_{ij} is computed by multiplying the normalised decision matrix by the normalised criteria weighting:

$$v_{ij} = w_j \times r_{ij} \tag{6-6}$$

where $i = 1, \dots, m; j = 1, \dots,$ n; m is the number of attribute value in each criterion, n is the number of criteria and w_j is the normalised weight of the jth criterion. $w_j = \frac{w_j}{\sum_{j=1}^{n} w_j}$ so that $\sum_{j=1}^{n} w_j = 1$, w_j is the original weight assigned to each criterion.

Step 4: Determination of positive and negative ideal solutions. The positive ideal solution (PIS) minimises the cost criteria and maximises the benefit criteria, whereas the negative ideal solution (NIS) does the opposite. The following equations are used:

$$A^+ = [v_1^+, \cdots, v_j^+, \cdots, v_n^+] \tag{6-7}$$

$$A^- = [v_1^-, \cdots, v_j^-, \cdots, v_n^-] \tag{6-8}$$

with A^+ denoting the PIS and A^- denoting the NIS. Note that for benefit criteria, v_j^+ is aimed to get the maximum and v_j^- to be minimum, whereas for cost criteria it should be the opposite.

Step 5: Calculation of the separation measures of each alternative from the PIS and NIS. The separation is calculated for each alternative before GIS layers S_i^+ and S_i^- are created. The formula used to find the separation from PIS is given as:

$$S_i^+ = \sum_{j=1}^{n} |v_{ij} - v_j^+| = \sum_{j=1}^{n} D_{ij}^+ \tag{6-9}$$

while the formula for NIS is given as:

$$S_i^- = \sum_{j=1}^{n} |v_{ij} - v_j^-| = \sum_{j=1}^{n} D_{ij}^- \quad (6\text{-}10)$$

Step 6: Calculation of the relative closeness to the PIS. The relative closeness to an alternative i to the PIS can be computed as:

$$C_i^+ = \frac{(S_i^-)}{(S_i^+ + S_i^-)} \quad (6\text{-}11)$$

where $0 \leq C_i^+ \leq 1, i = 1, 2, \ldots, m$.

Step 7: Rank the preference of alternative based on the relative closeness. Using the values of C_i^+ obtained in Step 6, a ranking can be made by arranging C_i^+ in a descending order, with the best sites are the ones with a higher value. Since they are closer to the PIS, they are more preferred and have a higher priority.

A comprehensive reference on the steps involved in TOPSIS and examples can be found in Jozaghi et al. (2018), Kaliszewski & Podkopaev (2016) and Sánchez-Lozano et al. (2016). In a work by Sánchez-Lozano, et al. (2016), they compared the usage of AHP with TOPSIS and ELECTRE-TRI (Roy & Bouyssou, 1991) to find the optimal solar PV sites in Spain. The reason for their selection was due to the ability of TOPSIS to compensate for the lack or excess in the criteria continuously, whereas ELECTRE-TRI functions in a discrete manner, similar to AHP.

The primary method of determining weightings for their criteria was AHP, before the results being ranked by either TOPSIS or ELECTRE-TRI. Although their final results from TOPSIS and ELECTRE-TRI do not completely coincide, some similarities were observed between the best results produced by TOPSIS and the results produced by ELECTRE-TRI (Sánchez-Lozano, et al., 2016). This means that either method is not stand-alone, as they are dependent on another method for weighting calculation, which can be determined subjectively based on the decision maker's opinion or objectively based on a mathematical approach.

One disadvantage of using TOPSIS is that there is a risk of rank reversal, where adding or deleting one or more alternatives will affect the final result and the ranking of the previously-ranked alternatives will change, as emphasised by Sánchez-Lozano et al. (2015). Another disadvantage of TOPSIS is that the use of Euclidean Distance does not consider the correlation of attributes. This means when two attributes considered are not independent of one another, the influence that one has over the other cannot be detected and lead to an invalid evaluation (Bondor & Mureșan, 2012). As such, it is difficult to weight correlated attributes and keep the judgement consistent (Velasques & Hester, 2013). This is especially crucial when evaluating many criteria. Due to the focus of TOPSIS for ranking and it requires an additional method to determine the criteria weightings, TOPSIS was not used in this research, despite a lot of research applying TOPSIS alongside another technique (Sindhu, et al., 2017; Villacreses, et al., 2017; Cavallaro, 2010; Huang, et al., 1995).

6.4.5 ELECTRE

Another MCDM method that is applicable in site identification studies is ELECTRE, a method first developed in 1965 (Yu, et al., 2018; Figueira, et al., 2005). The initial method was developed by Roy and colleagues and first published as a research report in 1966 (Benayoun, et al., 1966). As a method that has developed throughout time, the ELECTRE family supports three kinds of MCDM; choice problems (ELECTRE-I, ELECTRE-Iv and ELECTRE-IS), ranking problems (ELECTRE-II, ELECTRE-III and ELECTRE-IV) and sorting problems (ELECTRE-TRI) (Yu, et al., 2018; Figueira, et al., 2005).

The basis of the ELECTRE method is the outranking technique, whereby binary relations representing the preferences among pairs of alternatives are constructed instead of synthesizing utility functions (DCLG, 2009; Mousseau & Dias, 2004). In other words, pairwise comparisons are performed between alternatives and for each comparison, the degree of concordance and discordance is calculated. One option is said to outrank another if it outperforms the other on enough criteria with significant weighting (DCLG, 2009).

Several parameters and a non-trivial algorithm (meaning not obvious or straight forward) are essential to implement this method and although they are based on pairwise comparisons, they are not as straightforward as compared to AHP (Brunelli, 2015). The pairwise comparison process in ELECTRE is modelled using outranking relations ***S***, denoting "at least as good as". For two options ***a*** and ***b***, four situations may occur (Figueira, et al., 2010; Figueira, et al., 2005):

- ***aSb*** and not ***bSa*** → ***aPb*** (***a*** is strictly preferred to ***b***)
- ***bSa*** and not ***aSb*** → ***bPa*** (***b*** is strictly preferred to ***a***)
- ***aSb*** and ***bSa*** → ***aIb*** (***a*** is indifferent to ***b***)
- Not ***aSb*** and not ***bSa*** → ***aRb*** (***a*** is incomparable to ***b***)

A concordance index is used to model the concept of concordance and to validate an outranking ***aSb***, a majority of criteria in favour of this assertion must occur (Figueira, et al., 2010). The concordance index can be calculated for each pair of options as the sum of all the weightings for those criteria (DCLG, 2009).

The assertion ***aSb*** cannot be validated if a minority of criteria is strongly against this assertion. This is then known as discordance. The discordance index for the two options can be calculated as the ratio between the difference in performance level and the maximum observed difference in score on the criterion concerned. Therefore, if ***a*** performs better than ***b*** on all criteria, then the discordance index is zero. Furthermore, the discordance index is only of real value if criteria are almost of equal importance (DCLG, 2009). Both the concordance and discordance indexes are determined using preference and indifference thresholds, which are based on the principle of fuzzy logic (Wu, et al., 2016; Roy, 1990).

To bring the concordance and discordance indexes together for all the options, a (relatively large) concordance threshold and a (relatively low) discordance threshold need to be defined. If the concordance index of an option lies above the chosen threshold value and its discordance index lies below the threshold value, then the option is said to outrank another option overall (DCLG, 2009).

With the various extensions within ELECTRE, there is a lot of research that has applied this method. For instance, Wu et al. (2016) used ELECTRE-III to identify offshore wind farms in their research due to the reasonable construction of binary relations. They also claimed that ELECTRE-III conveys more information as compared to ELECTRE-I and ELECTRE-II (Wu, et al., 2016; Mousseau & Dias, 2004). They also introduced a new way of applying MCDM when there is incomplete information for decision makers, which is called the intuitionistic fuzzy method. Although their proposed method was shown to effectively aid their offshore wind farm identification, the fuzzy method somewhat produces a blurrier line and gives less clarity to the data assessed, as highlighted by Saaty & Tran (2007).

Other research investigated and compared ELECTRE to TOPSIS, weighted sum and weighted product methods in various criteria including consistency, ease of understanding and adaptation of decision type in an industrial perspective for the design of solar collector structure (El Amine, et al., 2014). They concluded that the ELECTRE method scored the lowest in all aspects compared to TOPSIS.

Despite some types of ELECTRE methods being able to check for consistency, accommodate a large scope of criteria and take uncertainty and vagueness into account, the method causes the strengths and weaknesses of the options to not be directly identified. Subsequently, the results and impacts cannot be verified (Velasques & Hester, 2013; Konidari & Mavrakis, 2007). The pairwise comparisons, determination of concordance and discordance processes to compute an overall performance score in ELECTRE are also difficult to explain in layman's terms, making the application more complicated to non-experts (Velasques & Hester, 2013; Hajkowicz, 2007).

Besides the unidentifiable strengths and weaknesses of the method and its complication, there are also concerns with the outranking approach that it relies on arbitrary definitions on what constitutes outranking and how the threshold parameters are set. The approach indirectly captures some of the realities of decision making, especially by downgrading options that perform badly in any criterion (DCLG, 2009). In terms of transitivity, Figueira et al. (2005) suggest that an outranking relation such as ELECTRE is not necessarily transitive; in fact, the intransitivity comes from two situations, Condorcet effect and incomparability between options. A comprehensive application of the ELECTRE technique can be found in (Brunelli, 2015; DCLG, 2009; Figueira, et al., 2005).

From the review comparing TOPSIS, AHP, fuzzy and ELECTRE, the author affirms that the ELECTRE method is the most complicated MCDM method to apply, due to its complex mathematical equations to be used for site identification analysis. This is an important consideration as the MCDM method applied in this research is intended to be transferable for future projects. For this reason and the basis of ELECTRE on fuzzy logic which relies a lot on uncertainty, ELECTRE was not applied in this research. The lengthy steps in each outranking process which are complicated when involving multiple decision makers also discourage its application.

6.4.6 AHP

The Analytic Hierarchy Process (AHP) is a structured method for analysing complex criteria in decision making based on hierarchical processes (Saaty, 1990). Different attributes or criteria at different hierarchy levels are evaluated using weights, which are determined by the user/decision makers (Feizizadeh & Blaschke, 2014; Tenerelli & Carver, 2012; Carver, 1991).

The AHP method was first proposed by Saaty (1980) as a way of comparing multiple criteria in pairwise comparisons to assign weighting to each criterion. The use of AHP was first integrated with GIS by Carver (1991) in his site identification study for the disposal of radioactive waste (Carver, 1991) and the same technique has been implemented in a plethora of research ever since (Al Garni & Awasthi, 2017; Asakereh, et al., 2017; Sindhu, et al., 2017; Ishizaka, et al., 2016).

Since its introduction in the early 1980s by Saaty, AHP has been applied complex decision making problems in various fields including innovation management and the built environment (Ali & Al Nsairat, 2009), construction materials (Kurda, et al., 2019), operational management (Macharis, et al., 2004), geology (Mallick, et al., 2018; Sambah, et al., 2018), urban sustainability assessment (Ameen & Mourshed, 2019) and medicine (Uzoka, et al., 2011). In energy planning, the effectiveness of AHP in developing appropriate weighting systems has been established by Ayodele et al. (2018), Al Garni & Awasthi (2017), Asakereh et al. (2017), Baseer et al. (2017), Sindhu et al. (2017), Ishizaka et al. (2016), Noorollahi et al. (2016), Watson & Hudson (2015), Uyan (2013), as examples.

In the AHP process, the method begins with the comparison of the evaluated criteria in pairs. This first step is also known as the 'pairwise comparison'. The comparisons are usually done in the form of a matrix with an n x n dimension, corresponding to the number of criteria evaluated. As illustrated in Table 6.2, the values of comparison a_{ij}, a_{ik}, a_{jk}, a_{il}, a_{jl} and a_{kl} are filled in the upper part of the diagonal, while the reciprocal values a_{ji}, a_{ki}, a_{kj}, a_{li}, a_{lj} and a_{lk} in the lower part. To compare the criteria using AHP, a scale introduced by Saaty (1994) is used. This is shown in Table 6.3.

As an example, for the matrix in Table 6.2, if criterion i is regarded as 'moderately important' when compared to criterion j based on the AHP scale in Table 6.3, then the relative importance for i is assigned a value $a_{ij} = 3$, which automatically makes the relative importance for j the reciprocal of the value with respect to i, $a_{ji} = \frac{1}{3}$. This process is repeated for all the criteria compared.

Table 6.2: AHP pairwise comparison matrix.

Criteria	***i***	***j***	***k***	***l***
i	1	a_{ij}	a_{ik}	a_{il}
j	a_{ji}	1	a_{jk}	a_{jl}
k	a_{ki}	a_{kj}	1	a_{kl}
l	a_{li}	a_{lj}	a_{lk}	1
Column sum	S_i	S_j	S_k	S_l

Table 6.3: AHP rating scale.

Scale	**Degree of importance**	**Reciprocal value**
1	Equally important	1 (1.00)
2	Equally to moderately important	1/2 (0.50)
3	Moderately important	1/3 (0.33)
4	Moderate to strongly important	1/4 (0.25)
5	Strongly important	1/5 (0.20)
6	Strongly to very strongly important	1/6 (0.17)
7	Very strongly important	1/7 (0.14)
8	Very strongly to extremely important	1/8 (0.12)
9	Extremely important	1/9 (0.11)

To find the weighting of each criterion, W_c, the values in the pairwise comparison matrix need to be normalised using equation (6-12) (Saaty, 1980):

$$W_C = \frac{a_{mn}}{S_m} \tag{6-12}$$

where a_{mn} is individual values from the matrix and S_m is the respective S_i, S_j, S_k *or* S_l values according to the column of criteria. This produces a matrix of normalised values, which can be extended as a table shown in Table 6.4. As the new values in each column are a proportion of the Column sum of the pairwise comparison, the sum of each column of the normalised criteria value is equal to 1. Sum for each row is then computed, whose summation is equal to the number of criteria evaluated. Afterwards, the ratio of Row sum is computed over the total number of criteria. This converts the ratio to decimal. This ratio can then be converted into weightings in percentage by multiplying by 100.

Table 6.4: Normalised criteria value.

Criteria	***i***	***j***	***k***	***l***	***Row sum***	***Row sum/n***	***Weighting %***
i	$\bar{a}_{ii}$	$\bar{a}_{ij}$	$\bar{a}_{ik}$	$\bar{a}_{il}$	*p*	*p/n*	W_i
j	$\bar{a}_{ji}$	$\bar{a}_{jj}$	$\bar{a}_{jk}$	$\bar{a}_{jl}$	*q*	*q/n*	W_j
k	$\bar{a}_{ki}$	$\bar{a}_{kj}$	$\bar{a}_{kk}$	$\bar{a}_{kl}$	*r*	*r/n*	W_k
l	$\bar{a}_{li}$	$\bar{a}_{lj}$	$\bar{a}_{lk}$	$\bar{a}_{ll}$	*s*	*s/n*	W_l
Column sum	**1**	**1**	**1**	**1**	**n**	**1**	**100**

Although the criteria weightings are obtained in the steps in Table 6.4, AHP has an additional step which is the 'consistency check'. This ensures there are no irregularities in the comparisons which lead to the final weightings. To execute the consistency check, firstly, the eigenvector for each matrix is calculated. The application of eigenvector is necessary in this step for representing the priorities associated with that matrix computed earlier and to account for the inconsistency in human judgement, provided that the inconsistency is less than or equal to a desired value (Saaty, 2003; Saaty & Vargas, 1984). The eigenvector for each matrix is computed by using matrix multiplication of each row of criteria in the pairwise comparison in Table 6.2 with the value in the *Row sum/n* column in Table 6.4, before being divided by the respective criteria's average score. For instance, to obtain the eigenvector of *j* (λ_j), equation (8-1) is used.

$$[a_{ji} \quad 1 \quad a_{jk} \quad a_{jl}]\ x \begin{bmatrix} p/n \\ q/n \\ r/n \\ s/n \end{bmatrix} \div q/n = \lambda_j \qquad (6\text{-}13)$$

The eigenvectors for all criteria are computed and summed to produce the maximum eigenvalue (λ_{max}). λ_{max} is also known as the average consistency. Afterwards, the approximation of the consistency index, *CI* is calculated using formula (6-14),

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (6\text{-}14)$$

where λ_{max} is the maximum eigenvalue of the pairwise comparison matrix and ***n*** is the number of criteria. Finally, the consistency ratio (CR) is computed using equation (6-15),

$$CR = \frac{CI}{RI} \qquad (6\text{-}15)$$

with *CI* being the consistency index and *RI* the random index. The consistency ratio measures how consistent a judgement is relative to large samples of pure random judgements, noted by the *RI*. The *RI* for different *n* values is given in Table 6.5. The random index functions as the ratio of consistency index divided by the average of consistency index values for comparison matrices of various sizes (Shyamprasad & Kousalya, 2019). The size of randomly generated comparisons can be as large as 500 (Godinho, et al., 2011; Saaty, 1994a). Table 6.5 shows that the random comparison matrix of *n*=2 has a consistency index of zero as there is only one comparison between criteria. By comparing the consistency index with the random index, the ratio of consistency of the pairwise comparisons can be determined.

Table 6.5: Random consistency index for various n values.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Once the criteria weightings are obtained using AHP and the consistency check executed with a value of less than 0.1 or 10%, the weightings are considered valid and consistent. The value 0.1 is set as the preferred value by Saaty to compensate for minor inconsistencies in human judgement (Saaty, 1994b). However, if the consistency ratio is equal to or more than 0.10, it indicates an inconsistent judgment (Malczewski & Rinner, 2015) and may not yield meaningful results (Chakraborty & Banik, 2006).

Literary works have identified a preference towards AHP over other MCDM methods for various reasons. One primary reason is the ability to use AHP for both qualitative and quantitative data to make subjective judgements (Uzoka, et al., 2011). The ability of the method to handle various types of data gives the method a broader application for different types of work. AHP also allows group decisions to be made by multiple decisionmakers and stakeholders (Ibid). The structure of AHP in hierarchy enables users to document all steps involved and replicate them in other applications (Ibid).

By letting decision makers to compare two attributes simultaneously in the pairwise comparison stage, AHP grants convenience in the elicitation of information (Velasques & Hester, 2013; Uzoka, et al., 2011). AHP also provides measures to check for the consistency of judgement and preferences through its final step, the consistency check (Uzoka, et al., 2011; Ananda & Herath, 2009). This step is an additional step in AHP that distinguishes it from other MCDM methods by examining the level of consistency to avoid human errors in making subjective decisions especially in the pairwise comparison stage.

Despite the different final step of consistency check, the overall AHP framework is similar to other MCDM techniques that include weighting, dominance and scaling (Velasques & Hester, 2013). Its ability to aid decision making for complex real-world problems without requiring intense data gathering and processing are further advantages of AHP that makes it a preferred technique to assess multiple criteria simultaneously (Velasques & Hester, 2013; Carrión, et al., 2008).

The possibility of AHP being applied in quantitative and qualitative analyses is also another advantage as it can offer ways for different types of judgement. It has been demonstrated in participatory planning involving MCDM in environmental contexts combining quantitative and qualitative criteria (Higgs, 2006). In quantitative analyses, rating, or absolute judgement can be used, whereas for qualitative analyses the pairwise or relative judgement can be used (Russo & Camanho, 2015; Wallenius, et al., 2008). Although different methods can produce similar results, Russo & Camanho (2015) claimed that the pairwise method is more accurate due to its comparative selection process through pairwise comparisons, whereas the rating method to be more efficient for cases with many alternatives.

Adoption of AHP in this research

As the objective of this research is to find ideal brownfield sites for RE installation by analysing multiple criteria, AHP was employed to determine appropriate weightings for the evaluated criteria. This is due to its relevance and the various advantages that it offers for qualitative decision making process. Besides the ability to be combined with the GIS spatial analysis, it also provides a high degree of flexibility, reliability and effectiveness through various applications in energy planning, either as standalone or integrated with other techniques, as performed by Al Garni & Awasthi (2017), Asakereh et al. (2017), Sindhu et al. (2017), Ishizaka et al. (2016), Noorollahi et al. (2016), Watson & Hudson (2015), Uyan (2013), Heo et al. (2010) and Carrión et al. (2008).

AHP is also a straightforward method, with clearly documented steps that anyone can follow (Velasques & Hester, 2013). For example, the approaches taken by this method and in particular the AHP-OS software adopted in this research are available as public documents (for instance, Goepel (2019; 2018)). As such, users can easily refer to the operations of AHP to understand the methods in the background. This also makes it advantageous for the transferable process model building in this research, as no mathematical experts needed in the decision making process employing AHP. Furthermore, AHP operations can be explained to decision makers easily during workshops without any difficulty. This contributes to a clearer and more transparent site prioritisation process.

Evolving from the original 7-point scale to the 9-point scale, the method is demonstrated to be flexible in providing results when clear judgement is made. The method can perform independently without relying on others, unlike TOPSIS or fuzzy models. Due to the various advantages of AHP and its suitability to this research, AHP was chosen as the MCDM method to produce criteria weightings before they are further analysed in GIS.

In this research, the newer 9-point AHP scale was used due to the flexibility of preference representation that the 9-point scale offers compared to the 7-point scale. The additional consistency check step is also very useful in terms of verifying the validity of pairwise comparisons, as qualitative judgements can sometimes lead to inconsistent numerical values.

The methods reviewed in this section are summarised and compared in Table 6.6.

Table 6.6: Comparison of MCDM methods, adopted from Velasques & Hester (2013).

	Strengths	**Weaknesses**
SAW	Criteria can be compensated using SAW, very intuitive to decision makers, involves simple calculation without complex computer programs.	Setting weightings manually may be difficult, estimates do not always reflect real situations, the result obtained may not be logical.
Fuzzy	Allows for imprecise input, insufficient information can be used for data analysis.	Difficult to develop, several simulations might be needed before it can be used.

Table 6.6 (continued).

TOPSIS	Simple process, easy to use, the same number of steps regardless of the number of attributes.	The use Euclidean distance does not account for the correlation of attributes, judgement is difficult to weight and consistency is difficult to be kept.
ELECTRE	Takes uncertainty and vagueness into account.	Complicated and tedious process for non-expert use, outranking process causes the strengths and weaknesses to not be directly identified.
AHP	Easy to use, scalable, not data-intensive, consistency check, hierarchy structure can accommodate problems of various sizes.	Interdependence between criteria and alternatives can cause problems, rank reversal problem, inconsistencies between judgement ranking may occur.

6.5 Applying the Method in the Geographical Context of Greater Manchester

To run a site analysis to identify suitable brownfield sites for RE, it is important to consider a region which has a considerable number of sites. This is to boost the potential of energy generated, as well as lower the cost of investment. It is also important to consider a region where data is widely available, without which the criteria selection cannot be completed and the spatial analysis cannot be performed.

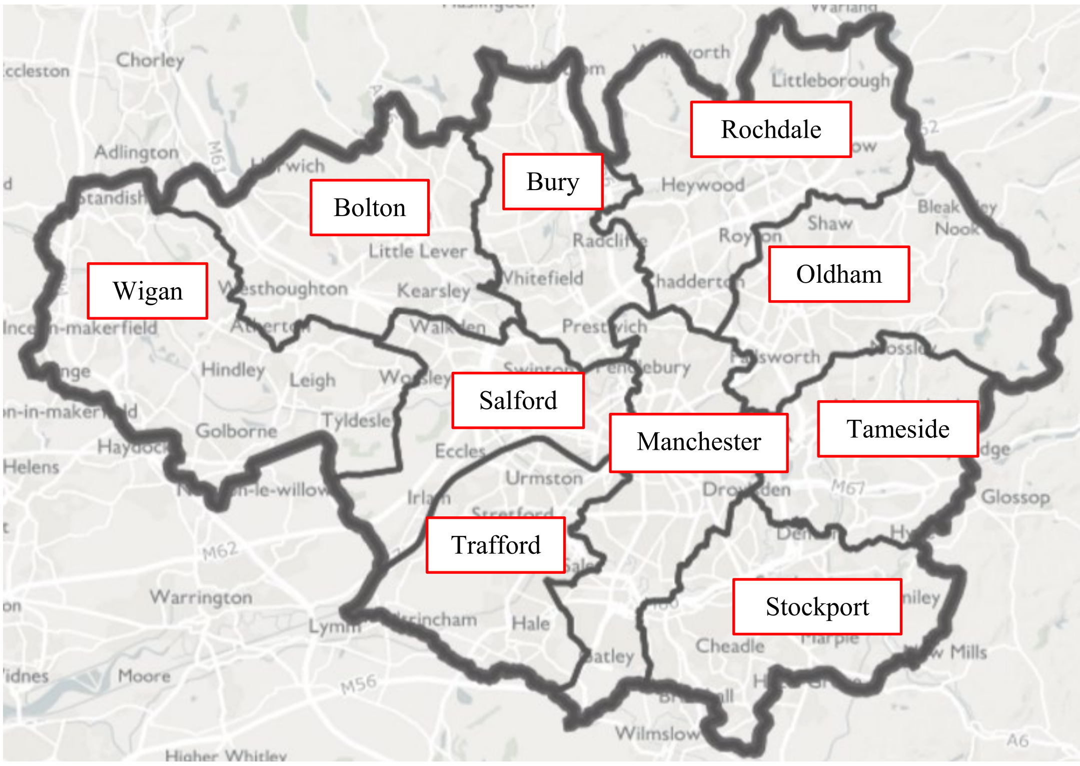
Based on the policy review, many developed countries have a strong interest in regenerating their brownfield sites, as well as promoting RE and heat. The same is happening in the UK with various policies in place (discussed in sections 2.5, 3.5 and 4.4). Many of the regions in the UK are rich in brownfield legacy due to the post-industrialisation effect. It is also vital to consider areas that are within proximity to urban areas to avoid energy loss in transmission or heat distribution from the energy generation sites (Sadovskaia , et al., 2019; NACAA, 2015; Wirfs-Brock, 2015).

One of the earliest industrial regions in the UK that was impacted by the post-industrialisation effect was GM. GM fits these criteria with a large number of brownfields, with 1,314 sites throughout the region and the largest number of sites located in Manchester (326), followed by Salford (211) (MappingGM, 2018). In terms of energy, the ever-growing urbanisation throughout GM increases the energy and heat demand day-by-day.

The location of brownfield sites around GM is largely dispersed making local energy generation more advantageous. For these reasons, GM was chosen for this research. Besides the availability of data from agencies in the UK that cover various aspects of site selection, the Greater Manchester Combined Authority (GMCA) also showed a strong interest in regenerating their brownfield assets through RE technology installations. This was informed by personal communication with the authority regarding their GM Spatial Framework. Despite their interest, they do not have any internal expertise.

One of the most urbanised boroughs in GM, namely Manchester, was also a case study in Dixon et al. (2010) when they compared Manchester and Osaka in Japan as it is the third-largest city in the UK with brownfield land. Similarly, research conducted by English Partnerships (2003) found that 25% of hardcore sites in England were in the North West of England, with substantial areas in Manchester and Salford. Hardcore sites are defined as sites suffering from long-term dereliction due to site-specific obstacles, such as contamination and fragmented ownership (Otsuka, et al., 2013).

GM comprises ten metropolitan boroughs; Bolton, Bury, Oldham, Rochdale, Stockport, Tameside, Trafford, Wigan and the cities of Manchester and Salford, as illustrated in Map 6.1. The population of GM is over 2.7 million, with around 530,000 people in Manchester (Office for National Statistics, 2015). This is another factor that influenced its selection for the case study. The positive annual population growth in GM can be correlated with the increase in energy demand. This is due to the modern city life within the borough that consumes an enormous amount of energy supplying on-going industries, education, construction and living. With the increase in demand, the supply of energy should ideally be sourced locally and sustainably to reduce the impact on the environment. One primary advantage of sourcing locally also helps reduce the loss of energy in transmission and distribution.



Map 6.1: Greater Manchester, with its 10 local authorities (Cabinet Office, 2017).

Besides the technical reasons for selecting GM as a case study area, the lack of published data on the GM area, whether in journal articles or theses, particularly for brownfield and RE motivated the author to select this region.

6.6 Spatial Data Gathering and Utilisation

Following the methodology and the area chosen for the research, the first step to the site identification process was the GIS data gathering. Various criteria were filtered based on the literature to determine if they were necessary to be applied to the renewable energy technology considered in this research. From the various criteria used in previous research, the relevant criteria were chosen and elaborated in sections 7.4 and 7.5.

The criteria were divided into two classes; restriction and evaluation. The restriction criteria are binary in function, with possible grades of 0 (indicating unfeasible area) and 1 (indicating feasible area), whereas evaluation criteria represent various levels of preferences/priorities. Once a restriction criterion was applied, the areas identified as unfeasible were excluded from the selection and no longer had any impact on the following stages of the site identification process. The complete process is elaborated in Chapter 8.

Brownfield GIS data were obtained from the Brownfield Land Register provided by MappingGM (2018). It is a compilation of all available brownfield sites from the 10 GM local authorities and was mapped in ArcGIS. For the restriction and evaluation criteria, various GIS criteria were considered. This process was very important in determining sites that can maximise energy generation while fully utilising the available area. A Digital Elevation Model (DEM) was obtained from the USGS website (USGS, 2017), which was then converted into the aspect and slope layers. The DEM from USGS was chosen for two reasons; the open-access files that can be downloaded directly from the website and the utilisation of USGS' DEM in the solar radiation model within ArcGIS (Huang & Fu, 2009). The 1 arcsec (30m) resolution of DEM was converted into aspect and slope; aspect was an important criterion for solar PV consideration while slope was important for WT.

Other technical parameters that needed to be satisfied were the level of 'fuel' available at each site and the area. For solar sites, these were solar radiation and for WT sites, these were wind speeds. The level of solar radiation for GM was generated using the Area Solar Radiation function within ArcGIS (Esri, 2016b). This accounts for various factors including aspect, slope, direct radiation and diffuse radiation.

For wind speed, data from the Global Wind Atlas were used, both at 50-m height and 100-m height for comparison. In Chapter 7, these two datasets were compared using maps and a similar pattern was observed in terms of wind speed in the area; the higher the observation point is the higher the wind speed. Therefore, to ensure the appropriateness of application for both large utility and smaller urban wind turbines, the data from 50-m height was used.

To optimise the brownfield space utilisation and maximise the output energy, site size was considered as an evaluation criterion, applicable to both solar PV and WT site selection. The size of each site was available in the brownfield GIS file, provided by the respective local authorities. This factor was regarded as important as large areas are needed for utility size WT, which have higher potential for energy generation. Similarly, more solar PV can also be accommodated in large sites to compensate for the spacing distance and to optimise the investment costs. Where smaller sites were prioritised, urban WT or rooftop solar modules can be put in place instead.

Due to the location of part of GM in the floodplain, the risk of flooding at potential solar PV and WT sites and potential to damage systems was taken into account and sites with lower flood risk prioritised. A flood risk map was used as an evaluation criterion, based on the Risk of Flooding Multiple Sources published by the Environment Agency (2017), which classified flood risks into 4 bands.

Due to the danger that large WT may pose to wildlife, some protected area categories were used as a restriction criterion. They dictate whether the available brownfield sites are feasible to be developed. The protected area categories used are the Special Protection Areas, Important Bird Areas, Special Areas of Conservation and Priority Habitats Inventory, obtained from Natural England and RSPB. These areas were combined to form one layer in ArcGIS, before a 500-m buffer zone was created. The buffer zone used was in accordance with the buffer zone applied in literature and policies, outlined in section 7.5.5.

Further data showing existing infrastructure that connect the sites were also analysed. This type of data included transportation (railways, roads, airports) and energy utility (electricity grid lines, substations). Airports pose a restriction for WT installation as they can interfere with the radio communications and complicate clearance. They can also cause a risk of glare to pilots when landing or taking off. As such, areas within airports were classified as restricted in this research. These data were extracted from the Ordnance Survey's (OS) Strategi.

The locations of electricity substations around GM were analysed as they also contribute to the investment costs in addition to direct costs. Spatial data for roads were based on the OS Open Road and the locations of the grid network and substations were based on National Grid and Electricity North West data respectively. Since all brownfield sites were once developed (as discussed in Chapter 2), their distance to road access and substations was observed to be only around 500 m and 300 m respectively. There is also no definite specification on how close a solar farm must be to the grid network (Palmer, et al., 2019); hence these criteria were not considered as evaluation parameters for this research.

A more comprehensive elaboration and justification of the criteria selected is available in Chapter 7 which helps to establish a clearer understanding of the criteria applied in AHP and ArcGIS. A complete list of datasets used, including their sources and publication dates are shown in Table 6.7.

Table 6.7: Datasets used in this research.

No.	Name	Source	Description	Spatial Coverage	Temporal Coverage	Aggregation Level	Format	Date published
1.	Greater Manchester Brownfield Land Register	GMCA (MappingGM)	Brownfield land register	GM consisting of 10 boroughs	Based on PBR, updated 21 Dec 2017	Greater Manchester Metropolitan county, borough, ward level	CSV	Dec 2017
2.	Region boundary line	GADM	Administrative boundary line for the whole UK.	England, Wales, Scotland, N. Ireland	2015 till current.	County, borough,	Shapefile	Nov 2015
3.	Digital Elevation Model (DEM)	EarthExplorer (USGS)	Digital Terrain Model/ SRTM.	Greater Manchester	Based on data collected in 2000	Res: 1 arcsec raster (approx. 30m) Size: 1-degree tiles	tiff	Sept 2014
4.	Grid Networks	National Grid	Datasets containing over-head line, tower, substation site, gas site, gas pipe and cable.	England and part of Wales	N/A	Individual sites, town/village/w ard level	Shapefile	May-Sept 2017
5.	Road Networks	Open Street Map Roads data	Complete road networks including major roads.	England	Updated daily, only the most recent files available.	Major roads, motorways, pedestrians,	Shapefile	Oct 2017

Table 6.7 (continued).

No.	Name	Source	Description	Spatial Coverage	Temporal Coverage	Aggregation Level	Format	Date published
6.	Solar radiation	Global Solar Atlas	Various types of radiation including GHI, DIF, GTI, DNI (all in kWh/m2) and PV power potential (in kWh/kWp).	Global	Different regions are covered from 1994, 1999 or 2007 up to 2015, updated yearly.	1 km x 1 km raster (30 arcsec)	tiff	Jan 2017
7.	Wind Speed	Energy Data	Global wind speed at 80m (low resolution).	Global	Oct 2016, updated in July 2017. No older data available.	3.7 km x 3.7 km grid	tiff	July 2017
8.	Strategi	Ordnance Survey	Attributes including airports, ferries, cities, towns, urban regions and other settlements and land use.	Great Britain	Last updated Jan 2016, no longer updated.	Site level, ward level	Shapefile	Jan 2016

Table 6.7 (continued).

No.	Name	Source	Description	Spatial Coverage	Temporal Coverage	Aggregation Level	Format	Date published
9.	Risk of Flooding Multiple Sources: Risk Band	Data.gov.uk	GIS raster layer showing risks of flooding from multiple sources, grouped into 4 bands. It indicates what areas of land may be at risk of flooding from more than one source considering risks from rivers, the sea and surface water.	England	Created on 13/6/2016 and last revised on 19/7/2017.	Ward level, not suitable for property assessment	tiff	Aug 2017
10.	Areas Benefitting from Defences	Data.gov.uk	This dataset shows those areas that benefit from the presence of defences in a 1% chance of flooding each year from rivers; or 0.5 % chance of flooding each year from the sea. If the defences were not there, these areas would flood in a 1% or 0.5 % or larger flooding incident.	England	Created on 1/1/2004 and last revised on 31/1/2018, updated quarterly, only most recent files available.	Ward level	Shapefile	Jan 2018

Table 6.7 (continued).

No.	Name	Source	Description	Spatial Coverage	Temporal Coverage	Aggregation Level	Format	Date published
11.	Priority Habitats North	Data.gov.uk Natural England	Geographic extent and location of Natural Environment and Rural Communities Act (2006) Section 41 habitats of principal importance.	North of England	Data added every year to the source file dated 1 Mar 1989, last updated in July 2014.	Individual habitat, ward level	Shapefile	Dec 2015
12.	Special Areas of Conservation	Data.gov.uk	Shapefile showing the land designated under Directive 92/43/EEC on the Conservation of Natural Habitats and Wild Fauna and Flora.	England	Created on 1 Jan 1970, last updated 24 Feb 2017.	Individual areas with conserved watercourse	Shapefile	Nov 2017
13.	Special Protection Areas	Data.gov.uk Data.gov.uk	Land classified under Directive 79/409 on the Conservation of Wild Birds. Data supplied has the status "Classified", and not including “proposed”.	England	Created on 1 Jan 1970, last updated 24 Feb 2017.	Individual area, ward level	Shapefile	Jun 2017

Table 6.7 (continued).

No.	Name	Source	Description	Spatial Coverage	Temporal Coverage	Aggregation Level	Format	Date published
14.	Important Bird Areas	RSPB	Conservation areas for bird habitats and migration paths.	England, Scotland, Wales and North Ireland	N/A.	Individual site, ward level	Shapefile	July 2017

6.7 AHP Application Using AHP-OS Software and Workshop

To complement the spatial analysis with the MCDM method chosen, AHP-OS, php based software developed by Klaus D. Goepel (Goepel, 2018) was used. AHP-OS is free online software developed and aimed for research and academia. It is well documented, freely available for any users of any level throughout the world and is transparent in its approaches.

With the easy-to-follow steps laid out on the website from the creation of the project until the final weighting elicitation, the software makes weight determination and AHP understanding easy for beginners. There are also open-access documents that guide users to the approaches or computations this open access software uses (for example, Goepel (2019, 2018)). Due to the numerous guiding documents available, it makes it easy for decision makers or local authorities to comprehend the software should they choose to implement this method and framework. A comparison of available AHP software in the market is outlined in Appendix D.

Using AHP-OS, a user can create online AHP projects, set the number of criteria and generate links to be distributed to participants. Having the ability to aggregate group decisions is an important consideration for selecting AHP software when involving multiple stakeholders or decision makers. Once each participant inputs their pairwise comparisons, a consistency check is performed before they can save their judgements. This is a crucial step to maintain an overall consistency in the final AHP value. The consistency ratio used by AHP-OS is based on the linear fit proposed by Alonso and Lamata (2006), which is based on the equation (6-16):

$$CR = \frac{(\lambda - n)}{(2.7699n - 4.3513 - n)} \tag{6-16}$$

where λ is the eigenvalue and n is the number of criteria. Their selection for this method of consistency ratio computation instead of the one proposed by Saaty is because this method can be used for evaluations of more than 10 criteria (Goepel, 2017).

Unlike other paid AHP software that is available on the market, AHP-OS has the advantage of aggregating group results using different scales. There are 10 types of scale that users can choose, which might alter the final weighting distribution slightly. This is not a flaw in its computation, rather it allows users to examine the best scale to use to derive the final criteria weightings. Although the weightings might be slightly different using different scales, the criteria priorities remain the same. The 10 types of scale that users can use are detailed in Appendix E.

Another important aspect besides the availability of different scales in the software is the ability of the AHP-OS to compute the degree of group consensus for group decision making. The

AHP-OS uses the Shannon entropy and its partitioning in two independent components (alpha and beta diversity) to derive the AHP consensus indicator (Goepel, 2017). Alpha diversity (H_α, D_α) indicates the average individual decision maker's priority distribution among criteria, whereas beta diversity (H_β, D_β) indicates the degree of variations of priority distributions among decision makers within the group. If a low variation is observed in the priority distribution, that indicates a high homogeneity and consensus within the group (Goepel, 2013). The indicator ranges from 0% (no consensus) to 100% (full consensus) and is categorized into very low, low, moderate, high and very high consensus (Goepel, 2018). Further explanation on Shannon entropy computation can be found in Al-Omar (2010).

For this research, AHP-OS was used to collect group opinions on criteria importance based on the AHP pairwise comparison. This was executed in two phases of workshops. This method was adopted as it provided a place for the introduction of research to the participants before they could begin with their individual task. It also acted as a space for interaction with other participants to compare their opinions on the important criteria in site identification for different technology. Some research also applied this method, for example, Lade (2013) and Neufville (2013), where they prepared a structured set of questions and allowed participants to fill them in a group environment.

During the AHP workshop participants were required to answer a structured set of questionnaires and rate the criteria importance, but for them to be able to answer using the AHP method correctly the AHP rating process and the steps of using AHP-OS were explained. The first phase which consisted of two workshops was held as a pilot study that collected opinions from PhD researchers within the University of Manchester. They were recruited from the Planning, Geography and Engineering departments as they satisfy the need for such experts in developments. A total of thirteen PhD researchers participated in the workshop, rated the criteria defined and answered a set of survey questions. The complete arrangement of the pilot workshop is elaborated in the following section 6.8.

The second phase of the workshop was the main MCDM workshop involving staff members at the Tyndall Centre, a staff member at the Estates services at the University of Manchester and MSc in Renewable Energy and Clean Technology students at the University of Manchester. These people were invited to participate due to their knowledge and expertise in the RE field. A full arrangement of the MCDM workshop is described in section 6.9.

6.8 The Pilot Workshop Arrangement

A pilot workshop was run to test the functionality of the AHP-OS software and the flow of process involving expert participants. It was also acting as the first step in the comparison of results using human-derived weightings with the weightings derived from the literature. The pilot workshop participants were recruited by email and personal communication sent to the entire departments. The Planning, Geography and Engineering departments were specifically chosen as the research needed insights from experts in the field, who know about the technical, geographical and planning aspects of RE installation.

At the beginning of the session, participants were briefed about the objective and significance of the research, the goal and the methods applied. The reason for selection of the criteria to be rated for the spatial analysis were elaborated. Participants were also informed of the AHP rating that they would need to perform.

After the introduction, they were sent an email with individual URL links to the solar PV criteria weighting, the WT criteria weighting and the survey. They were then allowed to answer them on their devices, either laptops tablets or phones. They were guided step by step on how to use the AHP-OS online software during the session to ensure that they followed the right steps to making judgements and the data input reflected their honest opinions.

Once they had completed comparing the criteria in pairs, they were also required to answer a set of questionnaires, which were set out as follows:

1. Name
2. Job role
3. Department
4. Why do you rate the criteria importance in such a way? For instance, flood zone the least important, solar radiation equally important to site size etc.
5. Are you willing to change your rating if you are influenced by additional information or if needed?
6. What other criteria do you think should also be considered?

The questionnaires were set on Select Survey, a University of Manchester approved survey platform. Each participant was invited to answer the same set of survey questions for the research to be able to relate the cause of the ratings to the participant’s opinions and background.

6.9 The MCDM Workshop Arrangement

Similar to the pilot workshop, the MCDM workshop was arranged by contacting prospective participants via email. Initially, the Greater Manchester Combined Authority (GMCA) was contacted via email, reaching out to the Director of Environment at GMCA, the Research Department and the general enquiry. However, no reply was received to that or a second email to each recipient. An email was then sent to the Regional Development Lead who responded and clarified their situation regarding their expertise in the RE field. Unfortunately, they did not have any in-house expertise in the utilisation of brownfield for RE development and they were looking for an external commission to evaluate their brownfield assets.

This led to a change of plan for the MCDM workshop. A new set of participants were identified through networking and based on their job role, working experience and course of study, they were invited to participate in the MCDM workshop. The invitation was extended to the Tyndall Centre for Climate Change Research, the Directorate of Estates and Facilities, and the cohort of MSc Renewable Energy and Clean Technology at the University of Manchester. Interested participants were required to register on Eventbrite. As the invitation was purposive including only people with knowledge in RE and brownfield, there were only eleven acceptance for the workshop of which six people attended and provided responses. They consisted of a sustainability project officer, a wind turbine expert, a mechanical engineering expert and three electrical engineers. Such a small number of experts was used in Sánchez-Lozano et al. (2016; 2015), Noorollahi et al. (2016a) and Neufville (2013).

The MCDM workshop was designed to resemble the pilot. Participants were first briefed about the research objective, significance and methods applied. Afterwards, the criteria considered in the research were introduced before they were informed of the AHP rating process. They were guided through the entire rating process, which was performed on URLs sent to their email. The ratings of importance are illustrated in Figure 6.4 and Figure 6.5. They were then required to answer the same set of questionnaires, as set out in the pilot workshop. The personal information requested was for analysis purposes to identify any pattern in decision making and any personal identifying information is not published.

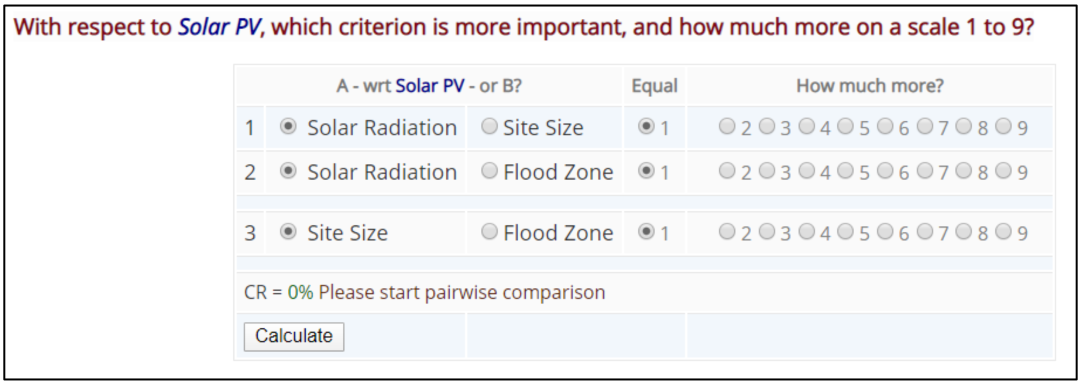


Figure 6.4: User rating page for solar PV criteria on AHP-OS.

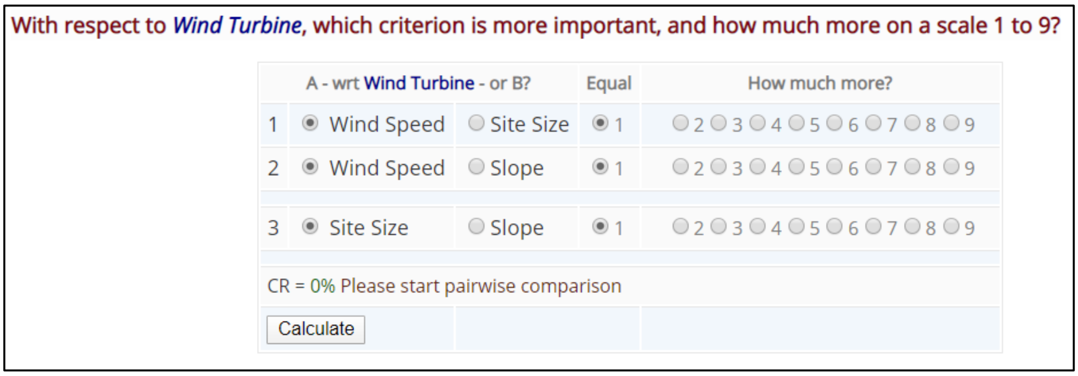


Figure 6.5: User rating page for WT installation criteria on AHP-OS.

6.10 Ethical Consideration

To execute the research, an ethics application was submitted to the Research Ethics team at the School of Environment, Education and Development to clarify the nature of research, types of participant involved and type of data collection. The ethical application also stated that the data collected will be used anonymously in the publication of results whether in thesis or journal articles. No personal identifying information will be revealed in the result presentation. During the workshop, participants were briefed on the nature of research and what data were collected about/from them. A copy of the consent letter was kept from each participant from all workshop sessions.

6.11 ModelBuilder

As mentioned earlier in section 6.4, Esri’s ModelBuilder was used in the spatial analysis. ModelBuilder is a built-in application in ArcGIS that can create, edit, manage and execute models which are made up of workflows. A typical model consists of an input, tool and output. The output of one tool can be fed into another tool’s input for further processing or used as a final output (Esri, 2016c).

At the end of the process, all criteria were combined to produce an output showing prime sites that reflect the weighting set by the decision maker. For this research, the standard input-output layout was used to build executable models for the two main steps; establishing a restriction layer and establishing an evaluation layer, which was then used to filter sites in stages.

ModelBuilder is very useful in executing iterative tasks as they can be automated to produce multiple results. It can also be easily transferred to be used on a different machine, as it is a compilation of many blocks of inputs and outputs, instead of re-building the steps from scratch. The ModelBuilder application is examined in more detail in Chapter 8.

6.12 Summary

To enable the execution of this research, this chapter began by placing renewable energy planning in the context of the sustainable city before it took a closer look at multicriteria decision making (MCDM), a method applied in combination with GIS. MCDM and GIS were also discussed in detail, beginning with the comparison of five MCDM methods and the justification on the method chosen. AHP, a branch of MCDM was utilised to obtain criteria weightings for solar and wind farm developments. This is due to the reliability of the AHP method in determining the suitability of brownfield sites for RE installations considering non-monetary factors.

This chapter then introduced the geographical area of Greater Manchester, where this method was employed. It then looked at the spatial data obtained and used in this research before outlining the flow of workshops and deployment of the AHP method. The AHP-OS software was used in conjunction with expert participation through a pilot workshop and an MCDM workshop to ensure the validity of the result produced.

Ethical considerations, problems encountered through the research and an introduction to ModelBuilder were also discussed in this chapter. Chapter 7 continues with the criteria for site selection to justify their relevance to the installation of solar PV, WT and GSHP. They are then narrowed down based on their relevance for brownfield installation before being rated by experts in the workshops and applied in GIS analysis in Chapter 8.

Chapter 7 : Criteria for Site Selection

7.1 Introduction

Chapter 6 outlined the methods applied to execute this research with the application of AHP-OS software in workshops to obtain criteria weightings for the spatial analysis which is discussed in sections 7.4 and 7.5. In this chapter, the locations of brownfield sites in Greater Manchester (GM) are first studied before the relevant criteria used in the AHP pairwise comparison are explained. The criteria for solar PV and WT are explained in detail based on the literature. For GSHP, this chapter discusses technical details for a typical GSHP placement to establish relevant criteria.

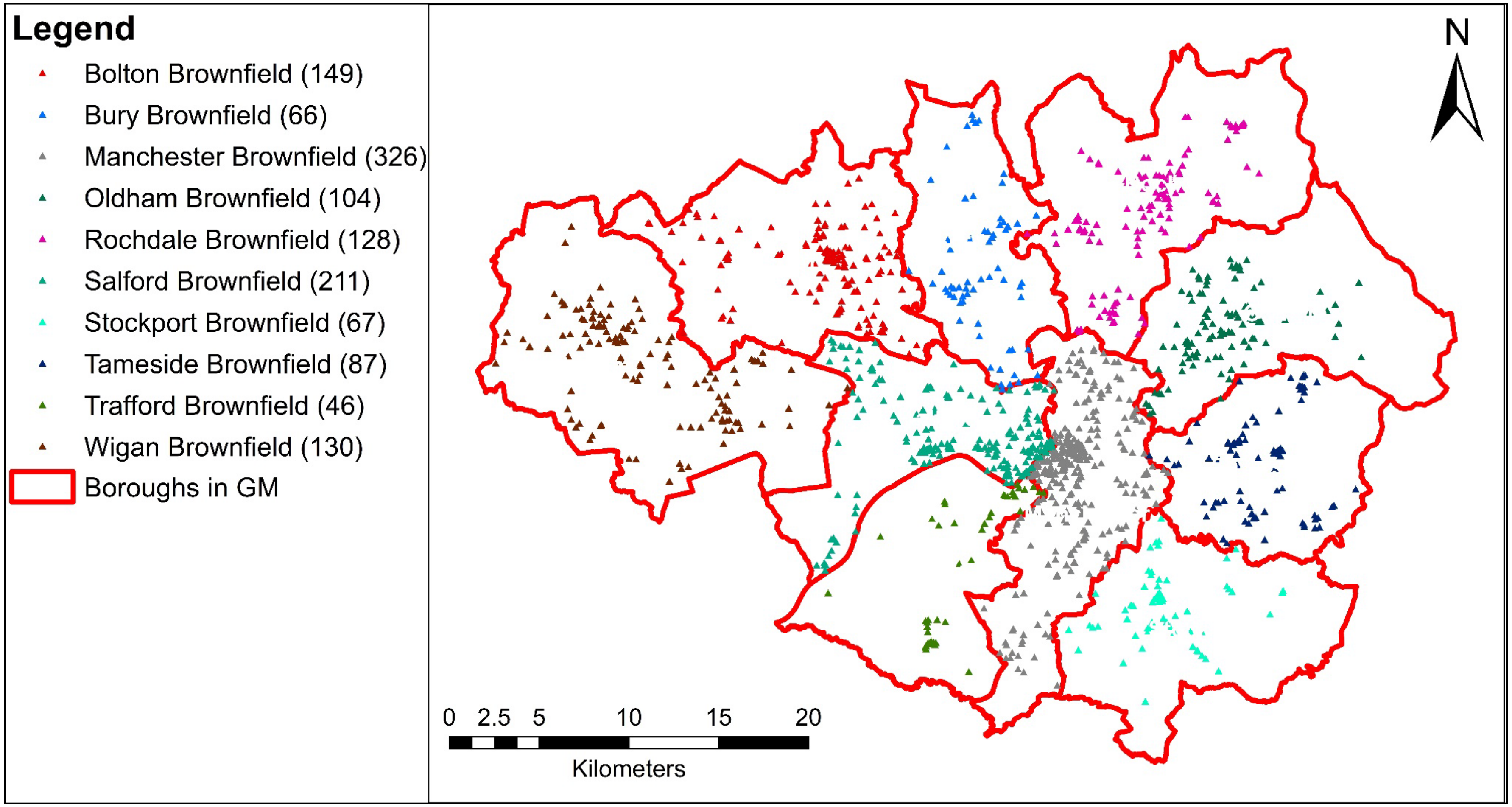
7.2 Brownfields in Greater Manchester

In GM, 1,314 brownfield sites were recorded in the Brownfield Land Register as of January 2018 (MappingGM, 2018), as shown in Table 7.1 and Map 7.1.

Table 7.1: Number of brownfield sites in GM boroughs (MappingGM, 2018).

Area	Number of sites	Percentage
Bury	66	5.0
Bolton	149	11.3
Manchester	326	24.8
Oldham	104	7.9
Rochdale	128	9.7
Salford	211	16.0
Stockport	67	5.1
Tameside	87	6.7
Trafford	46	3.5
Wigan	130	9.9
Total	**1,314**	**100**

The suitability for solar PV and WT installations was assessed separately due to the different criteria for each technology. They are elaborated in sections 7.4 and 7.5. This resulted in two suitability assessments. Brownfield sites were also evaluated for the GSHP installation using the criteria described in section 7.6 to optimise energy harvesting. They can host these technologies in the long run as solar panels can usually last for 25-30 years (Centre for Alternative Technology, n.d.). Whereas, WT can last between 20 and 25 years (Renewables First, 2015). This can provide a great solution for brownfield land outside urban areas or hardcore brownfields (brownfields that have been abandoned for a long time).



Map 7.1: Map showing brownfield sites across 10 boroughs of GM (MappingGM, 2018).

7.3 Selection Criteria for Site Identification

In guidance published by the Department for Communities and Local Government (DCLG), no hard rules are stated about how feasible areas for RE siting should be identified. Advice is given, however, to planning authorities to consider when applications are made for RE developments. These include taking into account the requirements of technology, potential impacts to the environment and the need to consider protected areas (DCLG, 2015; DCLG, 2013). Due to the relevance of the guidance to the context of this research, it was applied as the base in the judgement of criteria. The generalised guidance is also adaptable in other locations. Although most previously published planning guidance documents were superseded by the National Planning Policy Framework, the guidance supplied by DCLG has been adopted in the current planning guidance.

Based on the guidelines provided by DCLG combined with the preferred MCDM method elaborated in Chapter 6, the site identification process was conducted using relevant criteria for the GM context. The criteria were selected from the literature and evaluated to determine their significance for installations at brownfield sites. Section 7.4 focuses on criteria applied to solar PV, section 7.5 concentrates on criteria applied to WT and section 7.6 looks at technical details needed for GSHP installations.

7.4 Selection Criteria for Solar PV

A criterion is a measurable aspect of a judgment, which is used to describe and quantify options in a decision making process (Eastman, et al., 1998; Voogd, 1982). Identifying relevant criteria depends on the availability of the spatial data and the geographical coverage of the study area (district, national, regional, or continental). As this research was conducted on a regional level, the following selection criteria were of interest due to the relevance of sites, technology requirements and government regulations: protected areas, land cover, topography, flood areas, urban regions and sufficient solar radiation and wind resources.

Countries such as the UK and US have strict criteria protecting sites that are important in certain aspects, for example, sites of historic heritage or scientific sites. Hence, protected areas were excluded from consideration for renewable technology installations. However, unlike traditional projects where urban regions are restricted from PV installations due to aesthetic and noise concerns, this research considered urban and agricultural areas due to the potential of sharing sites. Flood areas were assessed in terms of the likeliness of flooding to occur annually to manage mitigation measures. Further explanations for each criterion are provided in sections 7.4.1 to 7.4.6.

Following the datasets obtained for GM (see Table 6.7), suitable brownfield sites were identified using ArcGIS based on the criteria and parameters used in previous research, summarised in Table 7.2, Table 7.8 and Table 7.12. The criteria were classified into 'restriction', which means no installation was allowed within specific conditions, and 'evaluation', which means installation was allowed if the requirements for the criteria were fulfilled. The 'restriction' class was Boolean, with possible options of 0 (unfeasible) and 1 (feasible), while 'evaluation' had a certain level of preference.

Once a restriction criterion was applied, the defined areas were excluded from selection and no longer had any impact on the following stages of site identification. Hence, it does not affect the sensitivity analysis to evaluate the effect of different weightings on the site evaluation scores. In this research, the evaluation criteria were rated using classes from 0.0 indicating unfeasible, to 1.0 indicating ideal condition. Table 7.3 outlines the criteria used for solar PV site identification in this research.

Table 7.2: Criteria considered for solar PV installation in the literature.

Criteria	Value used	Reference	Location of study	Type of criteria
Aspect/orientation	165° - 180°	(SolarPV, 2017)	UK	Restriction
	Southeast to southwest	(Watson & Hudson, 2015)	UK	
Slope	Max of 3% (or 1.72°)	(Aly, et al., 2017; Uyan, 2013; Hang, et al., 2009; Carrión, et al., 2008)	Tanzania, Turkey, China, Spain	Restriction/ evaluation
	Max of 5% (or 2.86°)	(Charabi & Gastli, 2011)	Oman	
	Max of 5.24% (or 3°)	(Cohen, et al., 2005)	USA	
	Max 5° (or 8.75%)	(Al Garni & Awasthi, 2017)	Saudi Arabia	
	Max of 11% (or 6.28°)	(Noorollahi, et al., 2016a)	Iran	
	Max of 10° (or 17.5%)	(Watson & Hudson, 2015; Baban & Parry, 2001)	UK	
Land cover	Non-agricultural land	(Sun, et al., 2013; Aydin, et al., 2010)	China, Turkey	Restriction
	Grades 1 and 2 should be avoided	(BRE, 2013; Baban & Parry, 2001)	UK	
	Use grades 3, 4 and 5	(Watson & Hudson, 2015)	UK	
Solar radiation	Minimum 5 $kWh/m^2/day$	(Sánchez-Lozano, et al., 2013)	Spain	Restriction/ evaluation
	Minimum 4.5 $kWh/m^2/day$	(Aydin, et al., 2013)	Turkey	
	Minimum 4.19 $kWh/m^2/day$	(Arnette & Zobel, 2011)	USA	
	Minimum global horizontal irradiation 3.5 $kWh/m^2/day$	(Anwarzai & Nagasaka, 2017; US EPA, 2015)	Afghanistan, USA	
	Observed and calculated average in England is 2.95 $kWh/m^2/day$	(Global Solar Atlas, 2016; Watson & Hudson, 2015)	Global, UK	

Table 7.2 (continued).

Criteria	Value used	Reference	Location of study	Type of criteria
Distance to grid networks	2 km	(Tegou, et al., 2010)	Greece	Restriction
	3 km	(Uyan, 2013)	Turkey	
	10 km	(Baban & Parry, 2001)	UK	
	50 km	(Noorollahi, et al., 2016a)	Iran	
Distance to substations	Depending on the capacity of existing nearby substations. New substations might need to be built for new farms	(US EPA, 2017; Aydin, et al., 2013; New Zealand Wind Energy Association, 2011; Carrión, et al., 2008)	USA, Turkey, New Zealand, Spain	Evaluation
Distance from urban areas/settlements	500 m	(Castillo, et al., 2016; Watson & Hudson, 2015; Uyan, 2013)	Turkey	Restriction
			Saudi Arabia	
	1.5 km	(Al Garni & Awasthi, 2017)	Iran	
	2 km	(Noorollahi, et al., 2016a)		
Distance from protected areas	500 m	(Uyan, 2013)	Turkey	Restriction

Table 7.2 (continued).

Criteria	Value used	Reference	Location of study	Type of criteria
Distance to main roads	100 m up to 1 km	(Uyan, 2013)	Turkey	Restriction/ evaluation
	1 mile maximum (1.6 km) for >300 kW	(US EPA, 2017)	USA	
	2 km	(Tisza, 2014)	USA	
	10 miles maximum (or 16 km) for >6.5 MW	(US EPA, 2015)	USA	
	10 km maximum	(Anwarzai & Nagasaka, 2017)	Afghanistan	
	50 km maximum	(Al Garni & Awasthi, 2017; Noorollahi, et al., 2016a)	Saudi Arabia, Iran	
Distance to flood-prone areas and rivers	100 m from rivers	(Carrión, et al., 2008)	Spain	Restriction
	400 m from rivers	(Baban & Parry, 2001)	UK	
	500 m from rivers	(Arnette & Zobel, 2011)	USA	

Table 7.3: Categorisation of criteria used for solar PV installation in this research.

Criteria	Type of criteria	Map layer category
Aspect	Restriction	Boolean (1/0)
Site size	Evaluation	Rated class
Solar radiation	Evaluation	Rated class
Flood zones	Evaluation	Rated class

7.4.1 Site Size

To fulfil the objectives of this research and contribute to the boost of RE deployment in a utility-scale, the size of brownfield sites where solar energy can be harvested plays an important role. This consideration is parallel to the recommendation by DCLG to identify sites with sufficient area to place solar PVs to harvest the required energy output from the system. Rectangular solar panels, whether small or large need a considerable area to be placed, considering the row spacing. This spacing is influenced by the tilt required for each panel to face the Sun to reduce shading effects and obtain optimum energy, which is determined by the latitude of the site.

The standard size of PV panels is 1.6 m x 0.9 m, which has an area of 1.44 m^2 (The Green Age, 2014). Based on the smallest size of brownfield in GM with an area of 0.1 hectare (ha) or 1,000 m^2, the maximum number of panels that can be placed at the site is 690 (not including the spacing due to panel tilt). Due to the tilt required, there will be fewer panels that can be accommodated. If bigger panels are used, a bigger inter-row spacing will be required to avoid shadow cast on the panels. On the other hand, if the biggest site (109 ha) or the second biggest site (76.7 ha) is utilised, a bigger capacity of around 100 times can be observed. To maximise the potential of energy harvested, larger sites were prioritised in this research.

The site size criterion was not used in most site identification studies as their options were usually the entire regions (for example, Al Garni & Awasthi, 2017; Aly, et al., 2017; Anwarzai & Nagasaka, 2017; Aydin, et al., 2013; Carrión, et al., 2008), however, it is appropriate to be considered when specific site sizes are known. A solar developer company, Kronos Solar, argued that only sites of 1 ha and above are developed as solar farms due to the expensive installation costs (Kronos Solar, 2013).

As this research considers brownfield sites that have been previously developed, have road access and grid connection within proximity, sites smaller than 1 ha can be developed. Size of brownfields in GM ranges from 0 to 109 ha as tabulated and rated in Table 7.4. The sizes were grouped in intervals due to the existence of various sizes. In GM, smaller sites can be found in a larger number than larger sites. As a result, larger sites were grouped together. A chart of a more detailed grouping is shown in Figure 7.1.

Table 7.4: Ratings of brownfield sizes.

Site size (ha)	No. of brownfield	Assigned rating
50.0 – 109.0	5	1.0
10.0 – 50.0	12	0.9
5.0 – 10.0	27	0.8
1.0 – 5.0	211	0.7
0.5 – 1.0	196	0.6
0.4 – 0.5	96	0.5
0.3 – 0.4	99	0.4
0.2 – 0.3	155	0.3
0.1 – 0.2	172	0.2
0.0 – 0.1	341	0.1

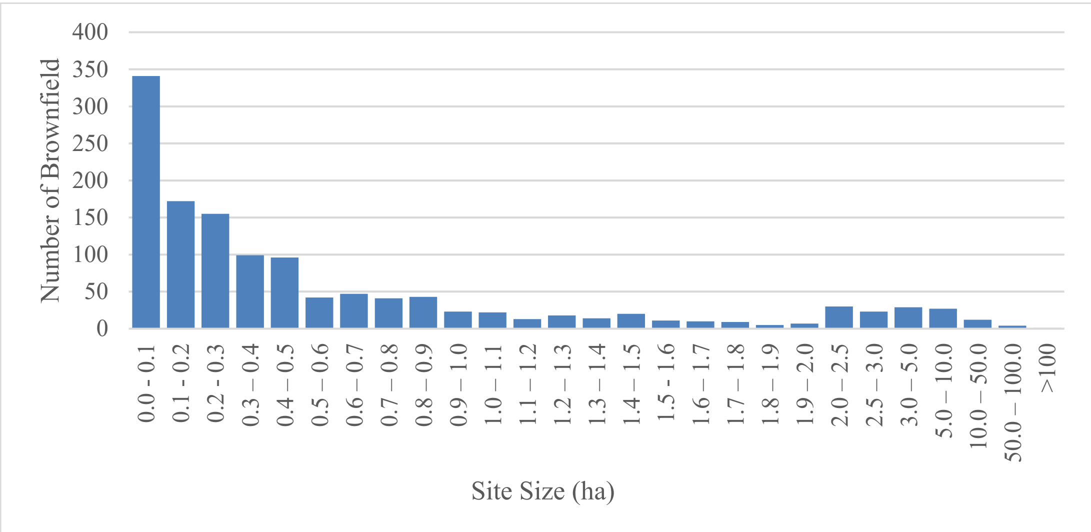


Figure 7.1: Brownfield sizes and count.

Another reason to favour larger sites is the economic factor to avoid unnecessary installation costs and other investment costs. This is linked to the economies of scale, whereby a large investment can be reduced with more units per installation. As a result, a larger installation may cost less than two installations at two smaller sites for the same total area. This may be due to the transportation and grid connection costs. Furthermore, with the potential of sharing site (for instance, with agriculture, later in section 7.4.5), it is beneficial to consider the site size as an evaluation criterion and to prioritise larger sites to accommodate the trade-off area (Adelaja, et al., 2010).

Economies of scale brings advantages to larger PV installations by spreading fixed project and overhead costs over a larger number of installed capacities. The bulk purchase of materials and larger project executions also contribute to economies of scale (Barbose, et al., 2018). As shown in Figure 7.2, the price of installed PV capacities for different scales has an inverse relationship with the increasing capacity, with the lowest price recorded for installations of more than 1,000 kW.

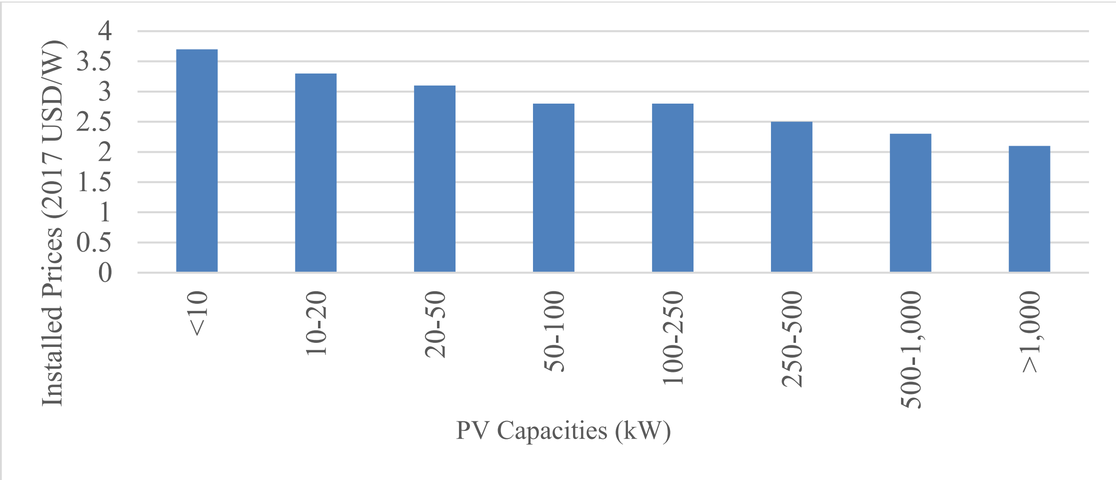


Figure 7.2: Installed prices for various PV capacities (Barbose, et al., 2018).

For this research, where solar panels can be deployed together with WT, combined construction may also benefit from economies of scale where costs of labour or materials can be shared for the two technologies. Executing projects this way can optimise brownfield potentials and hard and soft costs related to brownfield development (Barbose, et al., 2018).

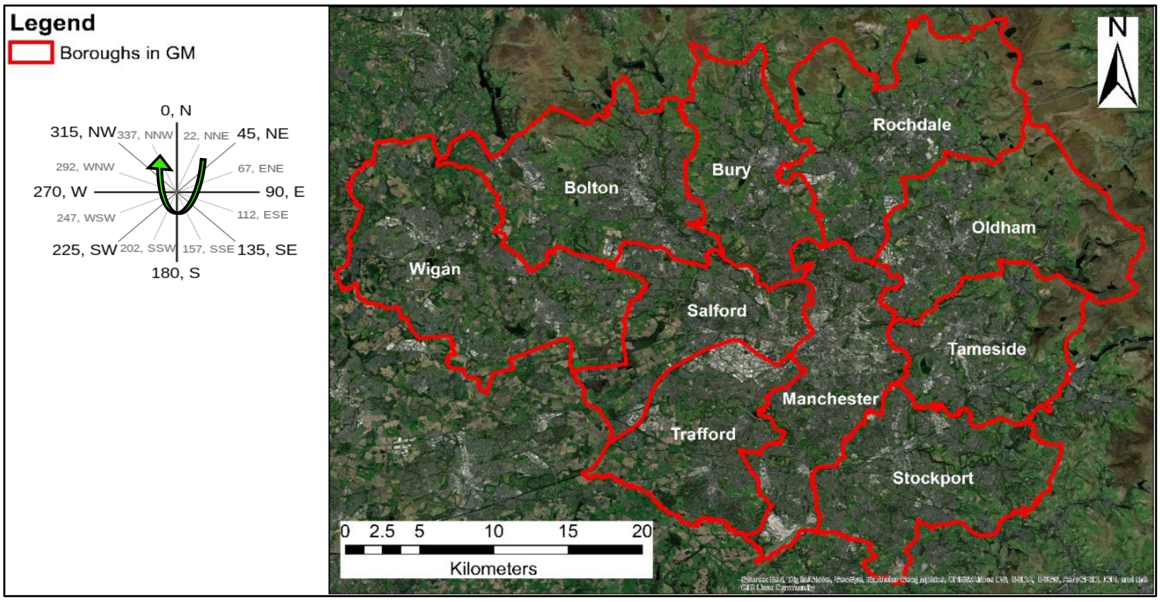
7.4.2 Aspect

The location of GM is in the northern hemisphere (latitude 53.41°, longitude -2.19°), where the ideal aspect for the solar farm's placement is 112.5°-247.5°, from east-southeast to west-southwest (The Green Age, 2017; Watson & Hudson, 2015; The Eco Experts, n.d.). The second-best option that can be considered for PV placement is in the range of 247.5-292.5°. This range is feasible due to the heat in the afternoon that can generate more energy compared to the morning (SolarPV, 2017; Brown, 2015; Perry, 2014). Hence, it is worth accepting more westerly angles with the right tilt of solar panels between 30° and 40° (Boxwell, 2017; Brown, 2015). This is also based on the economic factor of static solar panel usage which are cheaper to install and operate. A typical static panel costs around £2,000 to cover a space of 25 m^2 (The Eco Experts, 2018a; The Eco Experts, 2018b). However, at Dragons Breath Solar, a do-it-yourself tracking solar kit can be purchased at £845 for panel support of up to 1kWp (Dragons Breath Solar, 2018).

To assess the topography in GM, the aspect layer was generated by converting the Digital Elevation Model (DEM) obtained from EarthExplorer using the Aspect function in ArcGIS (USGS, 2017). Because aspect was considered in the ArcGIS Solar Radiation Tool as one of its primary components for computation (explained in Chapter 5), the aspect here was only regarded as a restriction criterion, which include the northern orientations of 0-22.5° and 337.5-360° (see Table 7.5 and Map 7.2). The reason was due to the least solar radiation that north-facing sites receive, especially when the site is highly sloped (Grana, 2016). However, the solar radiation value generated by the ArcGIS Solar Radiation Tool was the primary data to identify suitable sites due to the embeddedness of aspect and slope. This ensured the best aspect (azimuth) and sun angle (zenith) were considered in the computation of solar radiation.

Table 7.5: Categories of aspect.

Direction	**Angle (°)**	**Condition**
Flat	-1 – 0	Feasible
North	0 – 22.5	Unfeasible
Northeast	22.5 – 67.5	Feasible
East	67.5 – 112.5	Feasible
Southeast	112.5 – 157.5	Feasible
South	157.5 – 202.5	Feasible
Southwest	202.5 – 247.5	Feasible
West	247.5 – 292.5	Feasible
Northwest	292.5 – 337.5	Feasible
North	337.5 – 360	Unfeasible



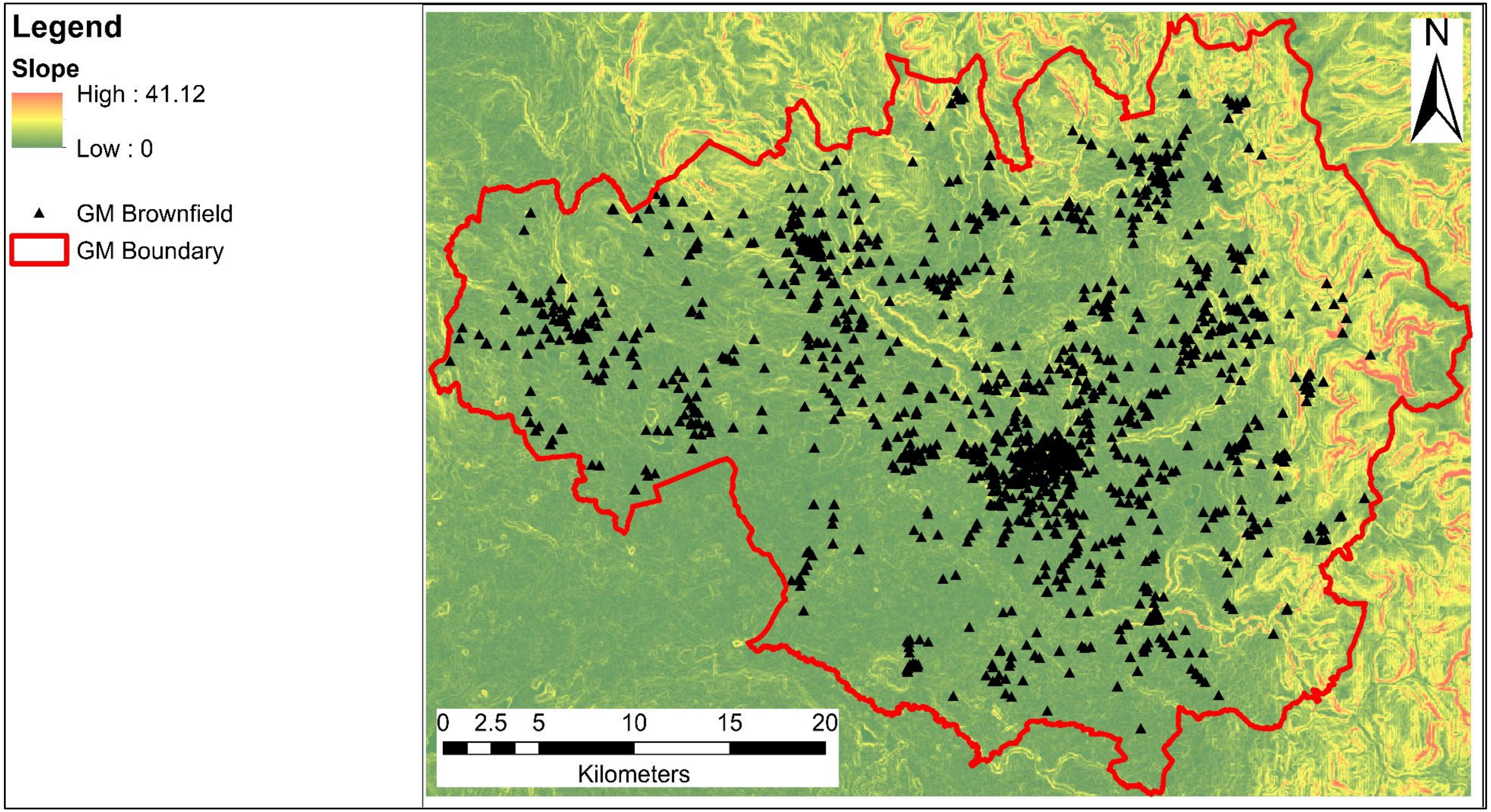
Map 7.2: Boroughs in GM with northeast to northwest bearing.

7.4.3 Slope

There is little agreement in research regarding the maximum slope for a solar farm installation, causing the lack of unified threshold of slope (Palmer, et al., 2019; Merrouni, et al., 2014). Despite the unavailability of information in this aspect, slope matters for developers and they prefer flat and semi-flat terrains as they are more exposed to sunlight. Such geography also has better constructability than steep areas that pose low economic feasibility (Al Garni & Awasthi, 2017; Aly, et al., 2017; Natural England, 2011). Different studies accept different slopes as suitable locations for solar PV installation, which is in a range of 2° up to 10°, summarised in Table 7.2. This is due to the latitude of the site that affects the position of the sun throughout the day and year.

Using the same method to generate the aspect layer in ArcGIS, slope was calculated using the Slope function using the same DEM input. The resulting layer shows that GM is generally built up by mostly flat areas of less than 41° (shown in Map 7.2). Significant sloped areas can only be found in the Pennines in the east of GM. As most solar panels need an inclination of 30°-40° for an optimum output, it is prudent to evaluate all brownfield sites considering GM has a natural inclination of less than 41°. This resembles the inclination of panels installed on rooftops (The Green Age, 2017).

Solar panels require less tilt to harvest the maximum solar radiation when installed on naturally sloped areas. This factor is only applicable when considering static solar panels, as tracking panels can capture sunlight from all angles. Due to the embeddedness of slope angle in the ArcGIS Solar Radiation Tool formula (Chapter 5), slope was not considered as a restriction or evaluation criterion for PV installation.



Map 7.3: Slope in GM. All regions have a slope of 41° or less (USGS, 2017).

7.4.4 Solar Radiation

The need to consider the amount of solar radiation received at specific sites is emphasised by DCLG in their guidance for selecting feasible solar sites (DCLG, 2015). However, no specific value was given as a minimum. Literature employs different minimum radiation values for an efficient and economic PV system (summarised in Table 7.2). This threshold value for solar energy resource varies from area to area, where a higher minimum is set for areas with higher average/annual irradiation. For example, in Sánchez-Lozano et al. (2013), 5 kWh/m^2/day was set as their minimum radiation for the southeast of Spain, whereas Aydin, et al. (2013) and Arnette & Zobel (2011) chose 4.5 and 4.19 kWh/m^2/day respectively as their minimum.

Due to the lack of clear guidance on what is acceptable in the UK (Palmer, et al., 2019), a comparison of average values is used. The average solar insolation increases from January to June and then reduces till December with a maximum insolation intensity around 5.11 kWh/m^2/day in June (Figure 7.4) (Solar Green Power, 2013). In the solar radiation maps (Map 7.4), the eastern region of GM has a slightly lower solar radiation compared to other areas due to its higher altitude and greater cloudiness in most months of the year.

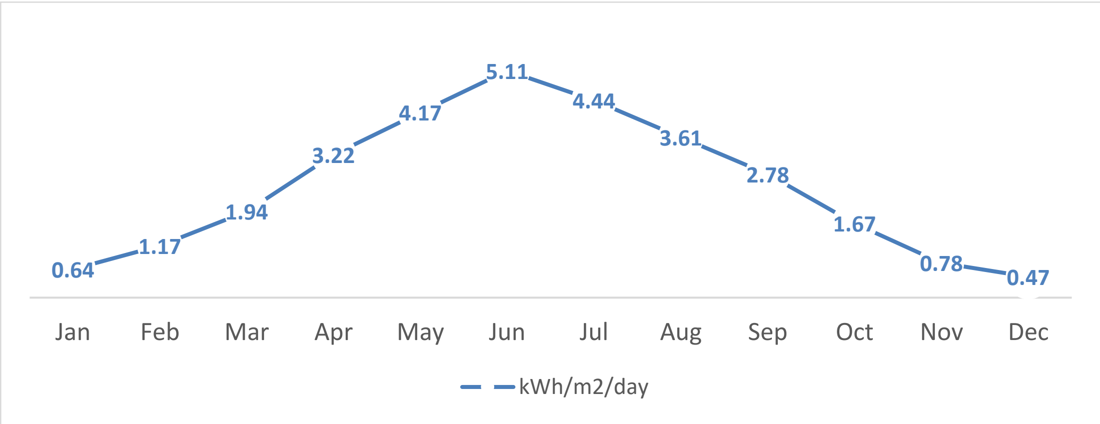


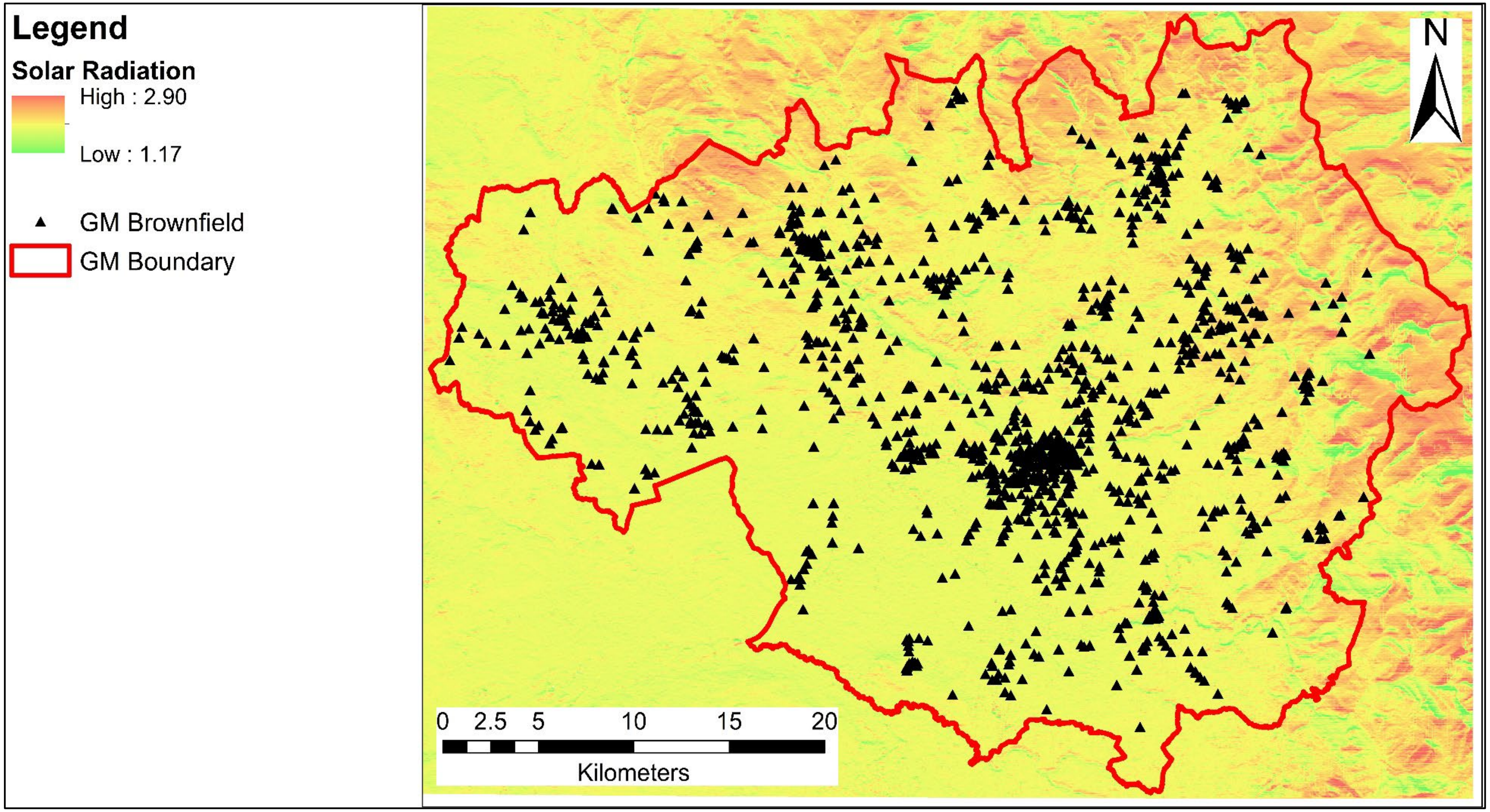
Figure 7.3: Solar radiation in the UK throughout the year (Solar Green Power, 2013).

Through GIS mapping, studying and assessing the radiation levels in various locations for different months is easier, especially for places without measurement equipment (Nematollahi & Kim, 2017). However, for places with no solar data available, estimations can be made in two ways; either with an interpolation technique or ArcGIS's Solar Analyst tool that can compute solar radiation using aspect, slope, diffusion, transmissivity and time interval.

There are different opinions on the linearity of distribution when classifying solar radiation, for example, Mierzwiak & Calka (2017) used a non-linear factor with a bigger middle interval of classification, whereas Mehos & Owens (2005) used a bigger interval for the highest class, indicating more sites are accepted in that class. Contrarily, Steadman (2019), Tegou et al. (2010), Carrión et al. (2008), Stewart (2008) and Stoddard et al. (2005) classed the solar radiation values linearly. In Table 7.6, the solar radiation values generated by ArcGIS are tabulated in a linear distribution.

Table 7.6: Classification of solar radiation levels using ArcGIS generated values.

Solar radiation ($kWh/m^2/day$)	**Assigned rating**
2.727 – 2.9	1.0
2.554 – 2.727	0.9
2.381 – 2.554	0.8
2.208 – 2.381	0.7
2.035 – 2.208	0.6
1.862 – 2.035	0.5
1.689 – 1.862	0.4
1.516 – 1.689	0.3
1.343 – 1.516	0.2
1.17 – 1.343	0.1
< 1.17	0.0



Map 7.4: The range of daily solar radiation generated by ArcGIS is between 1.17 and 2.9 kWh/m^2/day (Esri, 2016a).

7.4.5 Urban Areas, Protected Areas and Agricultural Land

Uyan (2013) suggested using 500 m as a buffer for urban, settlement and protection areas including forests, wildlife protection areas, biologically significant areas and environmental protection areas. The buffer acts as a restriction on those areas. However, considering that solar PVs are widely used in urban and settlement areas especially on rooftops of residences, no buffer area was assigned in this research. Solar panels can also be installed at agricultural sites if the agricultural usage of the land can be retained (Ownergy, 2011). Although arable usage is claimed to be difficult, a 'solar sharing' concept is adopted in Japan, whereby solar panels are installed above growing crops in a shared space (Figure 7.5) (Ho, 2013). The spacing between the arrays of solar PV allows enough sunlight to reach the plants for photosynthesis. Besides sharing croplands, solar farms can also provide habitats for endangered fauna such as wild birds and bees, whilst grazing remains possible within the raised PV arrays, as exemplified in Figure 7.6 (Natural England, 2011; Ownergy, 2011; Solar Trade Association, n.d.).

On top of that, the UK's planning policy on sustainable development recognises the need to support the diversification of agricultural land to help sustain an agricultural enterprise (Ownergy, 2011). Such a sustainable method of agricultural diversification is exemplified by the Kobern-Gondorf solar park in Germany that acts as a nature reserve for endangered flora and fauna (Ibid.). Effectively, all grades of land from Natural England's Agricultural Land Classification are viable to be used for solar harvesting so long as agricultural activities can remain.

Figure 7.4: Japanese 'solar sharing' farm (Ho, 2013).

Figure 7.5: Solar farms can provide grazing for farm animals (HyKoe, 2017).

7.4.6 Flood Areas

The proximity of potential sites to flood-prone areas is an important aspect that was factored in. Arnette & Zobel (2011), Carrión et al. (2008) and Baban & Parry (2001) recommended that RE farms to be at least 100 m away from rivers to protect them from flooding. In this research, a flood map combining multiple sources of flood and the risk level for each area in England was used (Risk of Flooding Multiple Sources (RoFMS): Risk Band). This map is a combination of the Risk of Flooding of Rivers and the Sea (RoFRaS) and the Risk of Flooding of Surface Water (RoFSW). It indicates the risk level with 1 being the highest up to 4 being the lowest (Environment Agency, 2017) (shown in Map 7.5). It covers flooding caused by rivers and sea, but does not include high groundwater levels, overland runoff from heavy rain and failure of infrastructure such as sewers and storm drains. The likelihood of flooding to occur is indicated in risk bands shown in Table 7.7.

It should be noted that RoFMS is different to Flood Zones as Flood Zones only consider flooding from river and coastal flooding but ignore the presence of flood defences. Whereas RoFMS measures the likelihood of flooding in an extreme event after accounting for flood defences (Groundsure, n.d.). Table 7.7 shows the likeliness of flooding to occur for each risk band alongside the number of brownfield sites in them, with 1,248 sites situated in the low and very low flood risk areas which is equivalent to 95% of the total available sites.

For the medium- and high-risk areas (above 1% chance of flooding), flood risk assessment (FRA) should be carried out to evaluate the chance and severity of flooding at a site level. However, if the area to be developed is in a 'very low' risk zone but larger than 1 ha, FRA is still required following the National Planning Policy Framework (MacLeod, 2015).

Table 7.7: Flood risk bands (Environment Agency, 2017).

Risk band	Likeliness of flooding	No. of sites	Adaptation measures
1 - High	Greater than 3.3% chance of flooding in any year	30	Flood risk assessment; guarded/high substations and PV placement to avoid flood
2 - Medium	Between 3.3% and 1% chance of flooding in any year	36	Flood risk assessment; guarded/high substations and PV placement to avoid flood
3 - Low	Between 1% and 0.1% chance of flooding in any year	150	Flood risk assessment; guarded/high substations to avoid flood if necessary
4 - Very low	Below 0.1% chance of flooding in any year	1,098	Feasible without mitigation.

As part of the FRA, a sequential test may need to be carried out to compare the proposed site to other available sites to identify the site with the lowest flood risk (Ministry of Housing, Communities and Local Government, 2019; DEFRA & Environment Agency, 2017). The test is intended to steer development to an area with lower risk when available. This is necessary if no prior sequential test was done to the site and it is in a medium- and high-risk flood zone. If there is no other lower risk site available, then an exception test must be done. An exception test shows how one will manage flood risk at their proposed site. It is only appropriate when the proposed site is a large area in a medium-risk or high-risk category where the sequential test alone cannot deliver acceptable sites. The main aim of the test is to demonstrate that the proposed development will provide wider sustainability benefits to the community and outweigh flood risk. The development will also need to be demonstrated safe throughout its lifetime and will cause no flood increase elsewhere (DEFRA & Environment Agency, 2017).

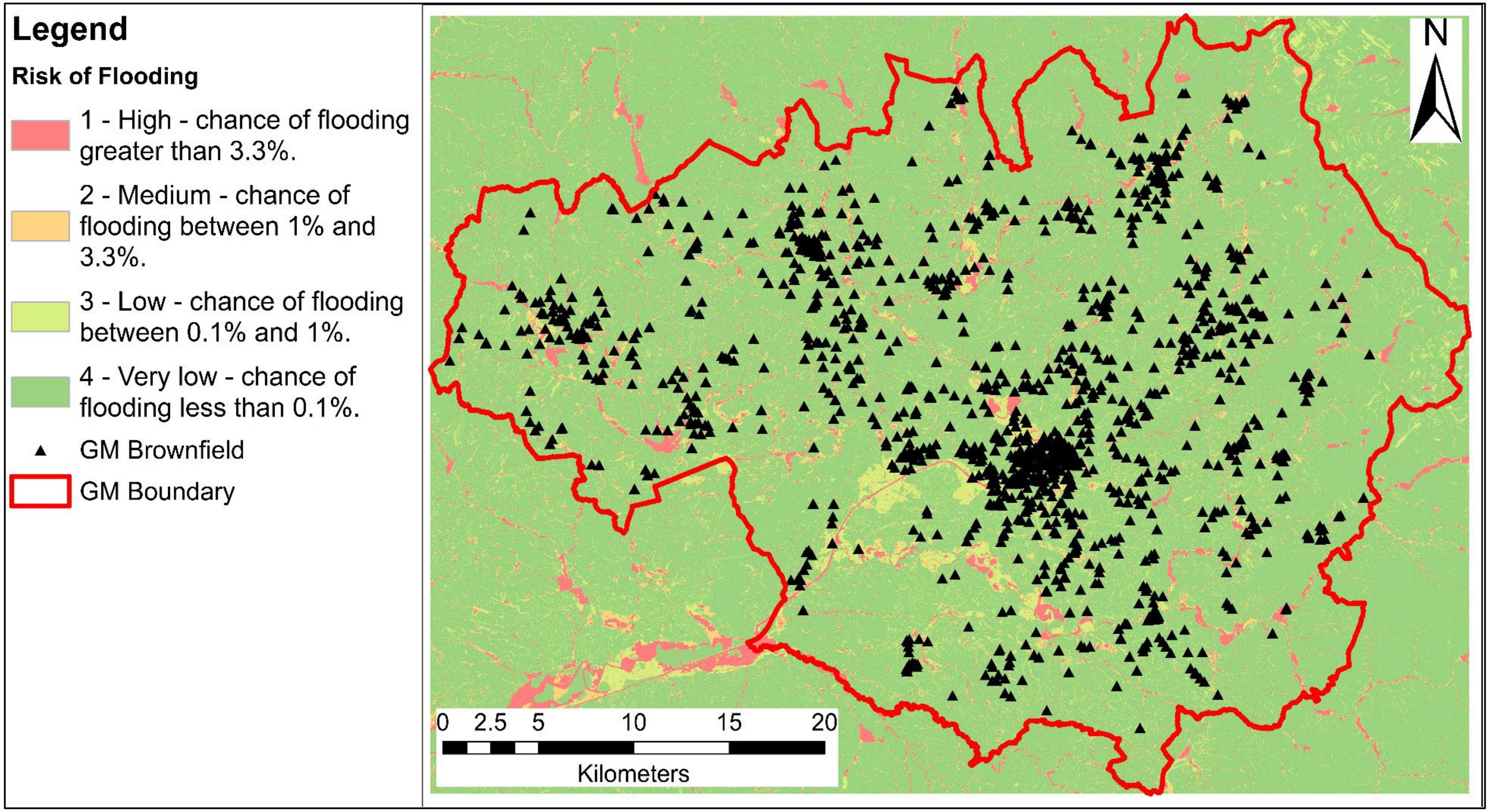
The Planning Policy Statement (PPS) 22 for Renewable Energy advises local authorities to not apply a sequential test for new RE projects (DCLG, 2009). Yet, a revision of the PPS25 states that utility infrastructure including power stations, grids and primary substations must satisfy the exception test before they can be built in high flood risk zones (DCLG, 2010). This effectively necessitates that solar farm, WT and respective substations to pass the exception test due to being categorised as ‘vulnerable developments’ (Ambiental, 2016). One interpretation argues and classes them as ‘essential utility’, or infrastructure that does not need to remain operational during flood times. Hence, classifying solar arrays as 'less vulnerable' and not vulnerable to flood risk stated in the PPS25, Table D.2 (MacLeod, 2015). Although solar panels can be classified as less vulnerable, concerns are commonly raised in various aspects regarding (UNDA, n.d.):

1. Location of inverter, transformer and substation within the floodplain;
2. Location of solar arrays within the floodplain;
3. Fencing and panels that might interfere with the free flow of floodwaters;
4. Increase of impermeable surface in the flood area;
5. Potential for increased surface water runoff.

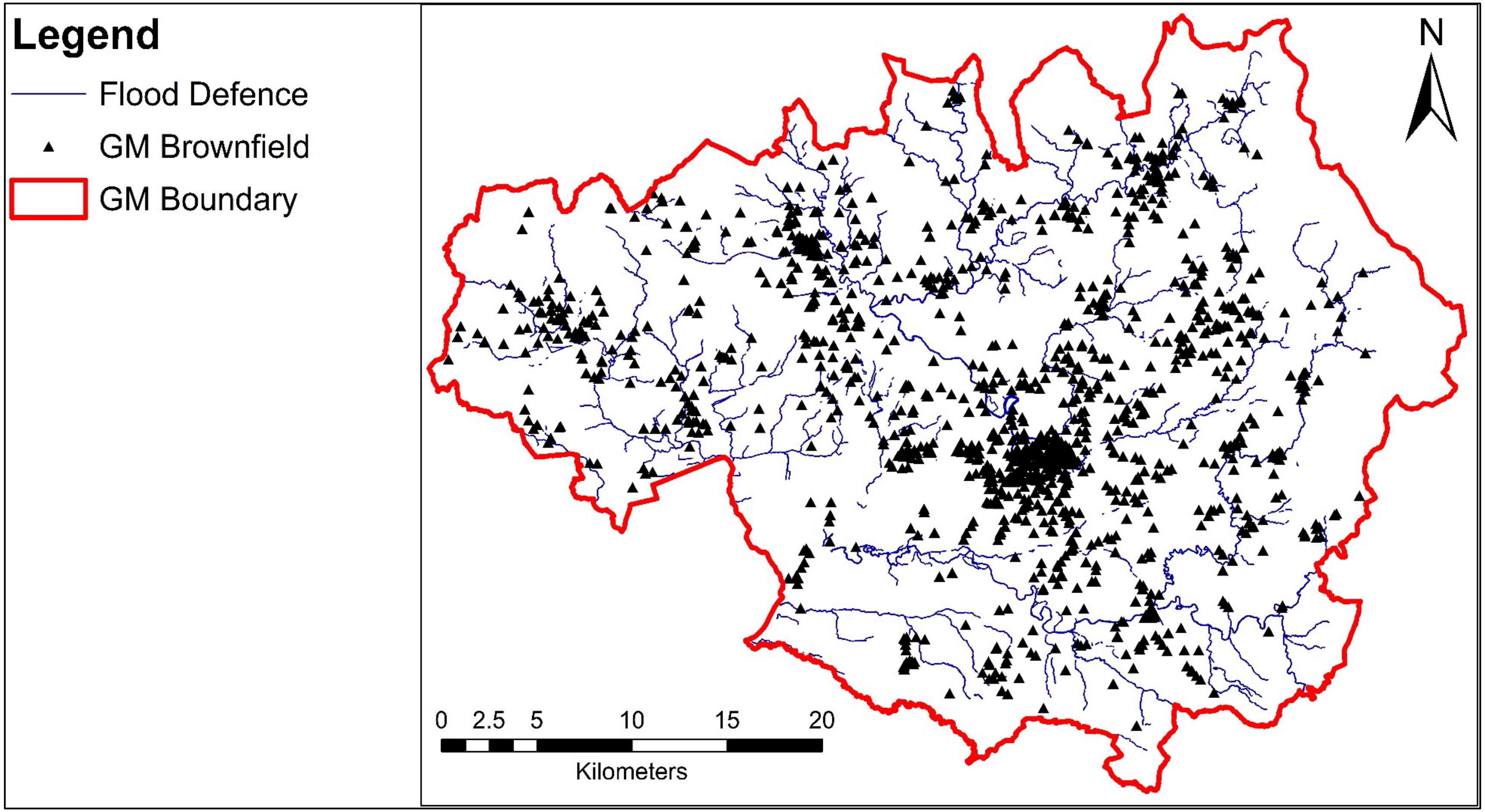
For developments in high-risk flood zones, safety measures need to be considered. For example, the most vulnerable parts of the development such as high voltage equipment and substations should be installed within the lowest risk of flood zone (Nijhuis H2OK, 2015; Ambiental, 2013; UNDA, n.d.). If this is not possible, they can be safeguarded from flooding and hydro-conductivity by locating them above the designated flood levels or providing better insulation (Ambiental, 2016; UNDA, n.d.). All cablings should be designed to be flood resilient/water-compatible using armoured cable and installed under the flood level. All these measures are parallel with the requirement stated in PPS25, para 4.55 (DCLG, 2009).

The height of the PV panels can also be raised higher than their usual height of 0.8 m above ground level to overcome the maximum flood level or above the 1 in 100-year flooding level and 300 mm freeboard (Nijhuis H2OK, 2015). By raising it higher, it can promote the 'solar sharing' concept, where arable agricultural activities and animal grazing can run. Access/egress outside of high-risk flood areas should be maintained where possible, otherwise, flood warning and evacuation plans should be provided. Flood mitigation should be incorporated to ensure that solar farms can remain operational and safe during flood occurrence. This includes building infiltration trenches to intercept flood flows and to create storage (UNDA, n.d.). There should be no new hard surface roads within the site to prevent impermeability (Ambiental, 2013), besides controlling the vegetation cover (Rankin, 2014).

Another data that functions alongside the floodplain map are the 'areas benefiting from flood defences' (Environment Agency, 2019; 2018). With the availability of embankments, flood gates, high ground, walls and demountable defences, sites located in the RoFMS regions are feasible for redevelopment provided the FRA is completed for those sites and flood defences remain intact and operational (Rankin, 2014). For GM, the flood defences are shown in Map 7.6.



Map 7.5: Map showing risks of flooding (Environment Agency, 2017).



Map 7.6: Flood defences in GM (Environment Agency, 2019).

7.5 Selection Criteria for Wind Turbine

Site selection for WT installations was done similarly as for solar PV. However, it only considered criteria corresponding to the requirement of WT without aspect and solar radiation threshold. There were more environmental factors involved instead, as illustrated in Table 7.8. Some studies (Sánchez-Lozano, et al., 2014; Uyan, 2013; Janke, 2010) regard locations further away from cities as more suitable for RE development to avoid environmental impact on urban development and 'not in my back yard' (NIMBY) oppositions. Furthermore, RE development in the city should be avoided to prioritise developments with higher profits.

Other research (Effat, 2014; Aydin, et al., 2013) indicate that sites near to city areas have more economic advantages. For this GM study, urban areas were not excluded as it was against the sustainable city objective. Additionally, there are green and urban-compatible solutions that integrate brownfield sites with built infrastructure suitable for WT deployments. Table 7.8 outlines the criteria used in the literature, some of which were adopted in this research. Like the solar PV criteria classification explained in section 7.4, the criteria for WT were also classified into 'restriction' and 'evaluation'. Table 7.9 outlines the criteria selected for this GM study.

Table 7.8: Site selection criteria for WT installation.

Criteria	Value used	Reference	Location of study	Type of criteria
Site area	1 km^2 for 2-4 MW	(Janjai, et al., 2014)	Thailand	Not applicable
	1 km^2 for 3 MW	(Musial, et al., 2016)	USA	
	1 km^2 for 4 MW	(Gaughan, 2018)	USA	
Slope	Max of 5° (or 8.75%)	(Al Garni & Awasthi, 2017)	Saudi Arabia	Restriction/ evaluation
	Max of 10% (or 5.7°)	(van Haaren & Fthenakis, 2011; Baban & Parry, 2001)	USA, UK	
	Max of 20% (or 11.3°)	(Grassi, et al., 2012; Hatziargyriou, et al., 2007)	USA, Greece	
	Max of 30% (or 16.7°)	(Zhou, et al., 2011; Tegou, et al., 2010)	China, Greece	
	Max of 40°	(Rodman & Meentemeyer, 2006)	USA	
Land cover	Non-agricultural land	(Aydin, et al., 2010)	Turkey	Restriction
	Grades 1 and 2 should be avoided	(Baban & Parry, 2001)	UK	
	Use grades 3, 4 and 5	(Watson & Hudson, 2015)	UK	
Wind speed	3-4 m/s minimum	(Jahangiri, et al., 2016; Yue & Wang, 2006)	Middle East, Taiwan	Restriction/ evaluation
	5 m/s minimum	(Centre for Sustainable Energy, 2013; Baban & Parry, 2001)	UK	
	5.5 m/s minimum	(Aydin, et al., 2013)	Turkey	
	6 m/s minimum	(Anwarzai & Nagasaka, 2017; Jahangiri, et al., 2016)	Afghanistan, Middle East	
Distance to grid networks	2 km	(Tegou, et al., 2010)	Greece	Restriction/ evaluation
	10 km	(Baban & Parry, 2001)	UK	

Table 7.8 (continued).

Criteria	Value used	Reference	Location of study	Type of criteria
Distance to main roads	240 m maximum	(Grassi, et al., 2012)	USA	Restriction/ evaluation
	2.5 km maximum	(Tegou, et al., 2010)	Greece	
	10 km maximum	(Anwarzai & Nagasaka, 2017; Miller & Li, 2014; Baban & Parry, 2001)	Afghanistan, UK	
	10 miles maximum (16 km)	(US EPA, 2015)	USA	
	50 km maximum	(Al Garni & Awasthi, 2017)	Saudi Arabia	
Distance to flood-prone areas	400 m	(Baban & Parry, 2001)	UK	Restriction
Distance from urban areas	350 m	(Barclay, 2010)	England	Restriction
	500 m	(Barclay, 2010)	Wales	
	2 km	(Anwarzai & Nagasaka, 2017; Nguyen, 2007; Baban & Parry, 2001)	Afghanistan, Vietnam, UK	
Distance from residential areas	500 m	(Uyan, 2013)	Turkey	Restriction
	2 km	(Barclay, 2010; Baban & Parry, 2001)	Scotland, UK	
Distance from airports	2.5 km	(Aydin, et al., 2013; Nguyen, 2007; Voivontas, et al., 1998)	Turkey, Vietnam, Greece	Restriction
	3.5 km	(US EPA, 2015)	USA	
Distance from special areas of conservation	500 m	(Yue & Wang, 2006)	Taiwan	Restriction
Distance from special protection areas	500 m	(Uyan, 2013)	Turkey	Restriction

Table 7.8 (continued).

Criteria	Value used	Reference	Location of study	Type of criteria
Distance from prioritised habitats	400 m	(International Energy Agency, 1987)	France	Restriction
	500 m	(Ramirez-Rosado, et al., 2008; Yue & Wang, 2006)	Spain, Taiwan,	

Table 7.9: Categories of criteria for WT siting in this research.

Criteria	Type of criteria	Map layer category
Protected areas	Restriction	Boolean (1/0)
Airport	Restriction	Boolean (1/0)
Site size	Evaluation	Rated class
Slope	Evaluation	Rated class
Wind speed	Evaluation	Rated class

7.5.1 Site Size

The size of conventional HAWT is usually more than 50 m and to install utility-scale WTs to feed into the electricity grid, large WTs are preferred. This requires large sites to host them. When a site hosts multiple WTs, spacing distance between them needs to be considered to prevent wake and turbulence that reduce the system's efficiency. Wake and turbulence are also problems for urban WT or VAWT. This factor is elaborated in detail in Chapter 3.

Similar to the criteria selected for solar PV deployment, there will be trade-off areas when installing multiple technologies. The foundation/base of a conventional HAWT need an area of at least 1,011.7 m^2 (1/4 acre or 0.1 hectare) (Adelaja, et al., 2010). This would utilise the entire brownfield site of this size. Consequently, larger sites are necessary to install such size of WT. Installing a WT on a site with solar PV will reduce the panel count due to this WT footprint. However, if the site has a high wind power density, more energy can be captured from this trade-off and this will be an advantage.

Another factor that affects the priorities of investment is the capital. Besides the financial requirement for land development, the connection to substations and transportation of WT also incur a significant cost. To reduce the costs and accommodate other factors, it is prudent to prioritise larger sites for development. Available sites were rated the same way as for solar development, shown in Table 7.4.

Farrell (2016) highlighted that changes in WT physical parameters can alter the wind energy production cost. For instance, doubling the height of a WT can reduce the electricity cost by 17%, whereas doubling the rotor diameter can decrease it even more, up to 75% of the original cost. To enable this, large sites are needed to accommodate a large turbine span. Moreover, a 25% increase in wind speed can reduce up to 37% of the cost. This means that more than a quarter of the cost can be saved by placing a WT in an area with a wind speed of 5 m/s instead of 4 m/s.

Although the wind speed parameter is not physically adjustable, higher wind speed can be achieved by placing a WT at a higher altitude, using large, clear sites with less obstructions or large sites with sufficient spacing. Furthermore, economies of scale show a substantial drop in installation cost per kW, as illustrated in Figure 7.7 (US Dept. of Energy, 2017). Economies of scale continue beyond 100 MW projects, although it was smaller. Thus, it is more practical to prefer larger sites over smaller sites.

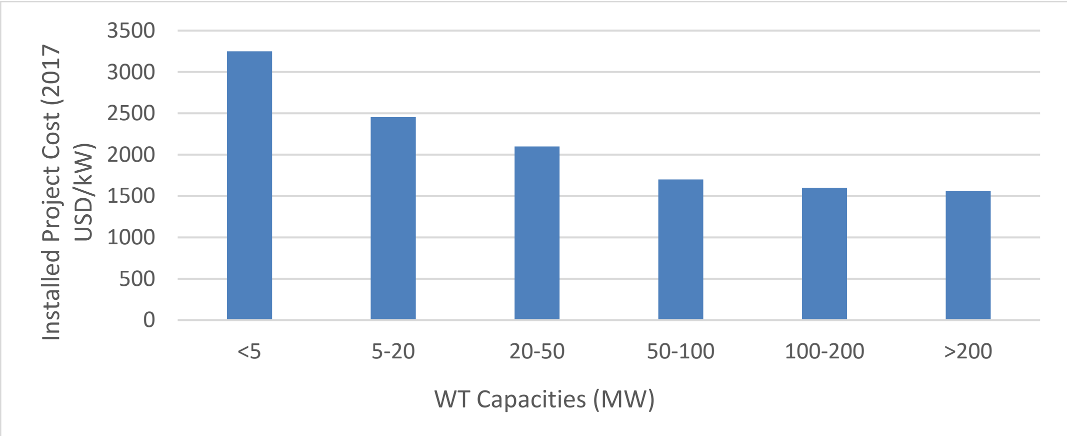


Figure 7.6: Cost of installations for WT projects of various capacities (US Dept. of Energy, 2017).

The need to prioritise larger sites is also due to the spacing distance between WTs. Research shows various ideal distances for WT placement. Yue & Wang (2006) prefer the spacing of 3 times the rotor diameter, Vattenfall (2013) prefer 5 times the rotor diameter and Gaughan (2018) prefer 7 times the rotor diameter. This means larger turbines require more space in between to prevent wake and turbulence. Otherwise, the operation of the turbines will be less efficient and yield lower output.

7.5.2 Slope

There are various opinions regarding slope for selecting WT sites. Some literature works prefer to use similar slope as for solar panels, whereas others prefer different slopes specifically for WT (as shown in Table 7.8). Some research did not factor slope in their site selection (for example, Baseer et al. (2017), Gorsevski et al. (2013), Rahman et al. (2012) and Aydin et al. (2010)). In studies where slope was considered, it was to assess the feasibility of installation, to design access tracks between turbine locations and to evaluate the cost involved to build a stable base for WT mast (Noorollahi, et al., 2016b; Vattenfall, 2013). This criterion should also be considered for health and safety reasons as installations on steep slopes are riskier due to the heavy and large WT components (Tegou, et al., 2010). Thus, slope was considered for this research.

The topography of GM is mostly flat with some areas having a slope of 41°. All sites were evaluated giving priority to flatter sites. Wind has higher potential energy over hilly terrain; energy recovers more quickly than over flat terrain, allowing for smaller spacing between turbines (Dominey, 2012). For building-integrated WTs in urban areas, the terrain slope imposes no influence on the site viability as they can either be installed flat on a roof or vertically on a mast. Table 7.10 shows the ratings for slope, adapted from Rodman & Meentemeyer (2006).

Table 7.10: Slope ratings for WT installation.

Slope (°)	Assigned rating
0 – 7	1.0
	0.9
	0.8
7 – 16	0.7
	0.6
	0.5
16 – 30	0.4
	0.3
	0.2
30 – 41	0.1
>41	0.0

7.5.3 Land Class

Much research restricts the development of wind farm to land classes 3, 4 and 5 (lower quality agricultural land) and non-agricultural land to avoid conflict of interest (for example, Watson & Hudson (2015), Aydin et al. (2010), Baban & Parry (2001)). There were also claims that WTs are dangerous equipment that should only be accessed by their owners and electrical experts. This is because heavy blades rotating high up in the air has the risk of dismounting and causing serious injuries or death, thus making WT sites unsuitable for combination with agricultural purposes (Kaiser & Fröhlingsdorf, 2007). Besides, the low frequency produced by WTs can affect humans' mental health, sleeping patterns and physical wellbeing although it is inaudible (Knapton, 2015).

With the steady growth of WT deployment, turbines have been installed in or nearby farms. Studies have been conducted to examine the effect of installing turbines around crops. They include mixing up the air that gives the crops more carbon dioxide. It was found to be advantageous for the photosynthesis process during the day while keeping the area warmer at night. Another advantage is that there is less dew at night, making the crops less prone to diseases caused by fungi (Inman, 2011).

To boost WT deployments, local authorities in the UK encouraged landowners and farmers to install utility-scale WTs on their land. This was due to the high percentage of agricultural land available in the UK, comprising of around 300,000 farms (Kinver, 2013; The Renewable Energy Hub, n.d.). When electricity is generated on farms, food production cost can be reduced. This is because the normal farming operations can resume once WT is installed and energy can be generated locally (New Zealand Wind Energy Association, 2011).

For livestock farms, good communication between farm owners and developers can leave a minimum impact on the animals. Sheep, cows and horses will not be disturbed by the WT and can usually graze up to the base of the turbine (Ibid.). With the safety features of modern WTs, co-siting concept like solar farms can be considered. It is practical to evaluate the potential of all land types to harvest wind energy without excluding agricultural land.

7.5.4 Wind Speed

The most crucial factor for selecting wind farms is the wind speed, as suggested by DCLG (2015) and DCLG (2013, p. 8), technology-specific criteria need to have a careful consideration to ensure optimum output is obtained from the RE installed. Wind speed varies due to factors including location, local weather and orography. It is not possible to forecast wind speed far ahead with any certainty. Hence, an average wind speed value is used to identify potential sites for wind farm development. Literature use different wind speed values as the minimum, ranging from 3 m/s up to 6 m/s (see Table 7.8).

A wind speed dataset is very useful if it is accurate, otherwise, an interpolation technique such as ordinary kriging[4], cokriging[5], inverse distance weighting[6] or point interpolation method can be used to extend a limited dataset to obtain data corresponding to a specific height (Sliz-Szkliniarz & Vogt, 2011). The data used in this research was based on the wind speed measurement at a 50-m

[4] Kriging is a point interpolation method that requires a point map as input and returns a raster map with estimations and optionally an error map. The estimations are weighted averaged input point values. The weight factors in kriging are calculated in such a way that they minimize the estimation error in each output pixel (Spatial Analyst, 2018a).

[5] Similar to kriging, but cokriging is a multivariate variant of the ordinary kriging operation. It calculates estimates for a poorly sampled variable with the help of a well-sampled variable. The variables should be highly correlated, either positive or negative (Spatial Analyst, 2018b). Cokriging requires much more estimation, including estimating the autocorrelation for each variable as well as all cross-correlations (Esri, 2019).

[6] Inverse distance weighting explicitly assumes that things that are close to one another are more alike than those that are far apart. It uses the measured values surrounding the prediction location to predict a value for any unmeasured location. Values closest to the prediction location have more influence on the predicted value than those far away (Esri, n.d.).

height. It has a minimum wind speed of 3 m/s in the urban areas of GM (illustrated in Map 7.7) (Global Wind Atlas, 2018).

This 50-m dataset was used instead of the ones at 100 m or 200 m as it was more suitable for small-scale or VAWT installations at lower heights. This type of WTs has a lower cut-in speed, making the data appropriate. Higher wind speeds are observed at higher altitudes (Map 7.8), indicating a proportional increase of wind speed with height. This shows suitability for larger or horizontal WTs.

The Centre for Sustainable Energy (2013) and Baban & Parry (2001) suggested a minimum wind speed of 5 m/s although 5-6 m/s is considered relatively low for commercial WTs and sites with 6-7 m/s wind speed should be prioritised to ensure a larger return on investment (Renewables First, 2015). However, for most commercial HAWT, the operating speed is between 3 m/s and 16 m/s as extremely strong winds will pose danger to the overall structure of the WT and its surrounding (Enercon, 2015). Beyond the safe operating speed of 34 m/s, the WT will use its pitch control to put one of the blades in the feathered position to put to allow the WT to run in idle mode.

It is a different case for urban VAWT that can be found in many shapes and sizes (as discussed in Chapter 3). With structures that can cope with higher wind speeds due to the different axis which the blades rotate in, VAWT has a broader range of operating speed. For example, the IceWind CW model has a range of operating speed of 2 m/s up to the cut-off speed of 50 m/s (IceWind, 2017). With such an ability to cope with extreme and gusting wind speeds, VAWTs need fewer safety measures as compared to HAWTs. As such, no minimum wind speed was selected to identify suitable brownfield sites for WT placement as there is potential for VAWT installation with very low cut-in speed. Furthermore, WTs can be installed higher to capture more energy, for example, on a taller mast or taller building.

The generated wind power is a cubic function of the wind speed in miles per hour (The Green Age, n.d.). For example, for a wind speed of 5 mph (2.2 m/s), the generated energy would be $5^{3} = 125$ kWh, and for 11.2 mph (5 m/s), the output would be 11.2^{3} = 1,405 kWh. The proportion of wind speed to the generated energy in Watts can be written as:

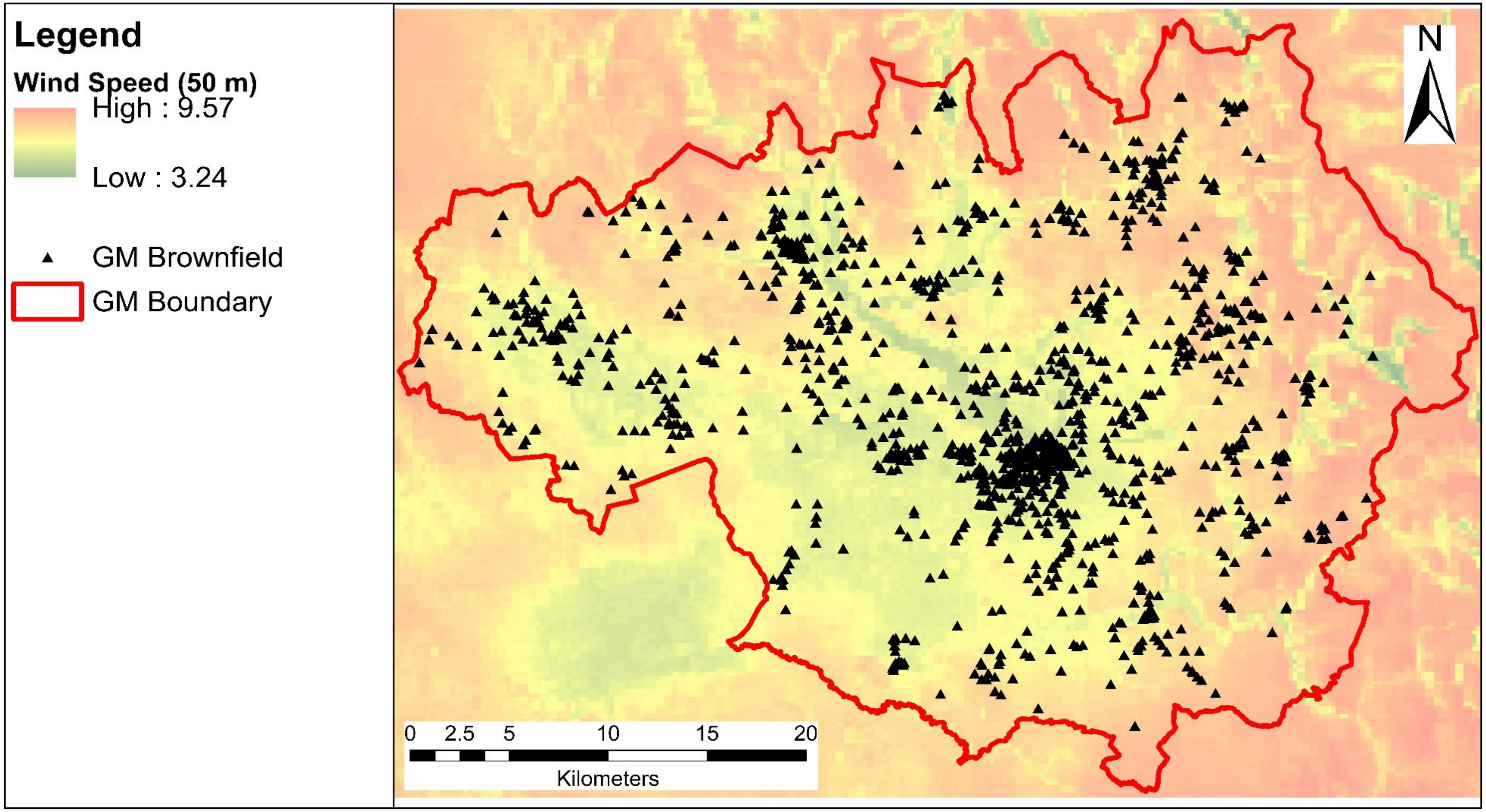
$$P(v) = \frac{1}{2} A \rho v_m^3 \tag{7-1}$$

where $P(v)$is the average wind energy in Watt (W), ρ is the air density in kg/m^3, A is the swept area of WT rotor in m^2, and $v_m$is the average wind speed in m/s (Ayodele, et al., 2018). The energy generated is influenced by the cubic function of wind speed, air density and the rotor swept area.

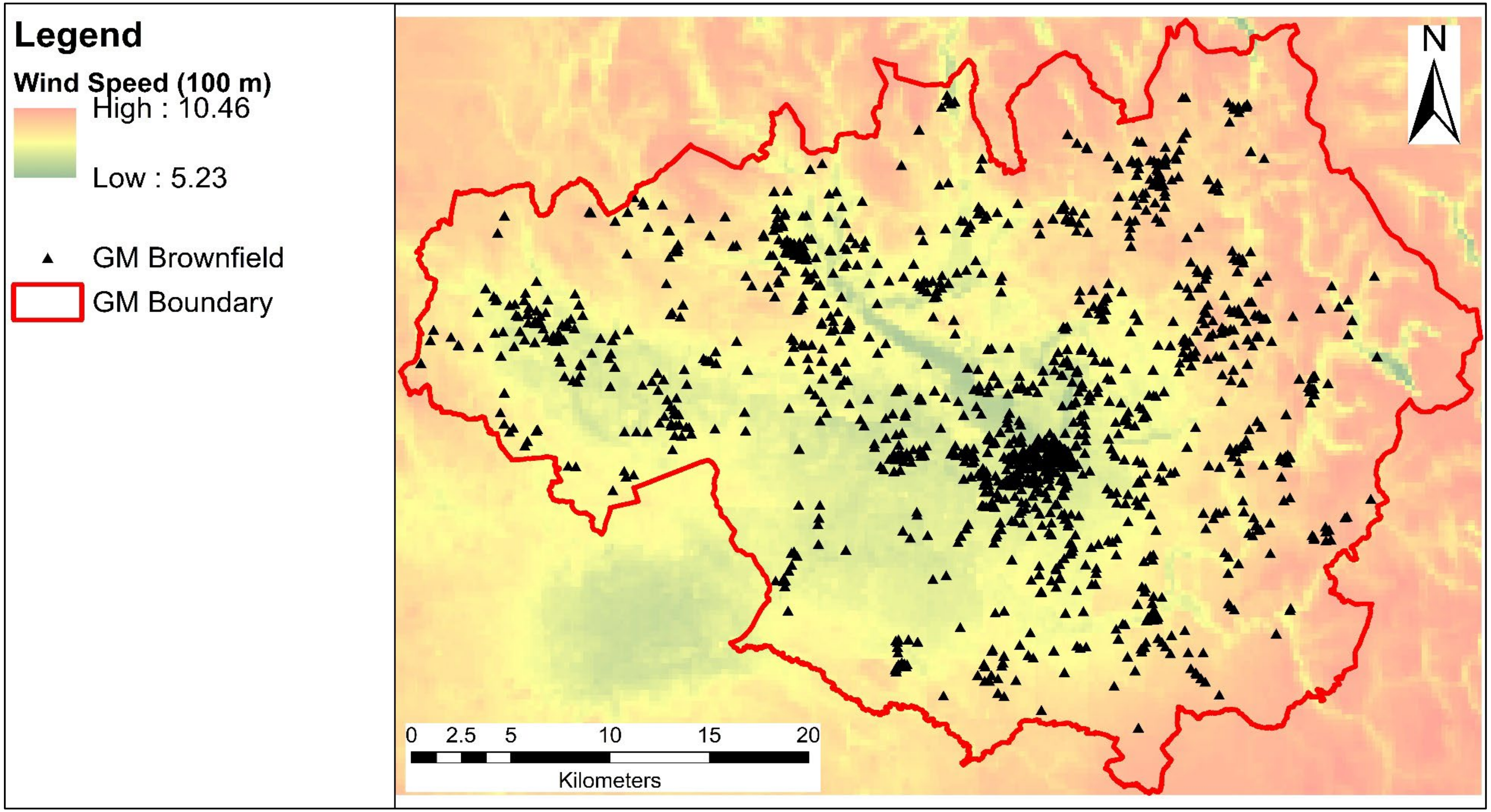
Adopting a common method to identify suitable wind sites applied in various literature (for example, Anwarzai & Nagasaka (2017); Jahangiri et al. (2016); Aydin et al. (2013); Centre for Sustainable Energy (2013)), natural wind speed data was used. The final brownfield scores using these data were compared with the results using cubic values of wind speed. The results produced better scores using the natural data. The data were categorised into 10 classes and rated linearly in intervals shown in Table 7.11.

Table 7.11: Wind speed classes based on Global Wind Atlas (2018) data.

Original wind speed (m/s)	**Assigned rating**
8.94 – 9.57	1.0
8.31– 8.94	0.9
7.68 – 8.31	0.8
7.05 – 7.68	0.7
6.42 – 7.05	0.6
5.79 – 6.42	0.5
5.16 – 5.79	0.4
4.53 – 5.16	0.3
3.90 – 4.53	0.2
3.27 – 3.90	0.1



Map 7.7: Wind speed at 50 m height for GM, in m/s (Global Wind Atlas, 2018).



Map 7.8: Wind speed at 100 m height for GM, in m/s (Global Wind Atlas, 2018).

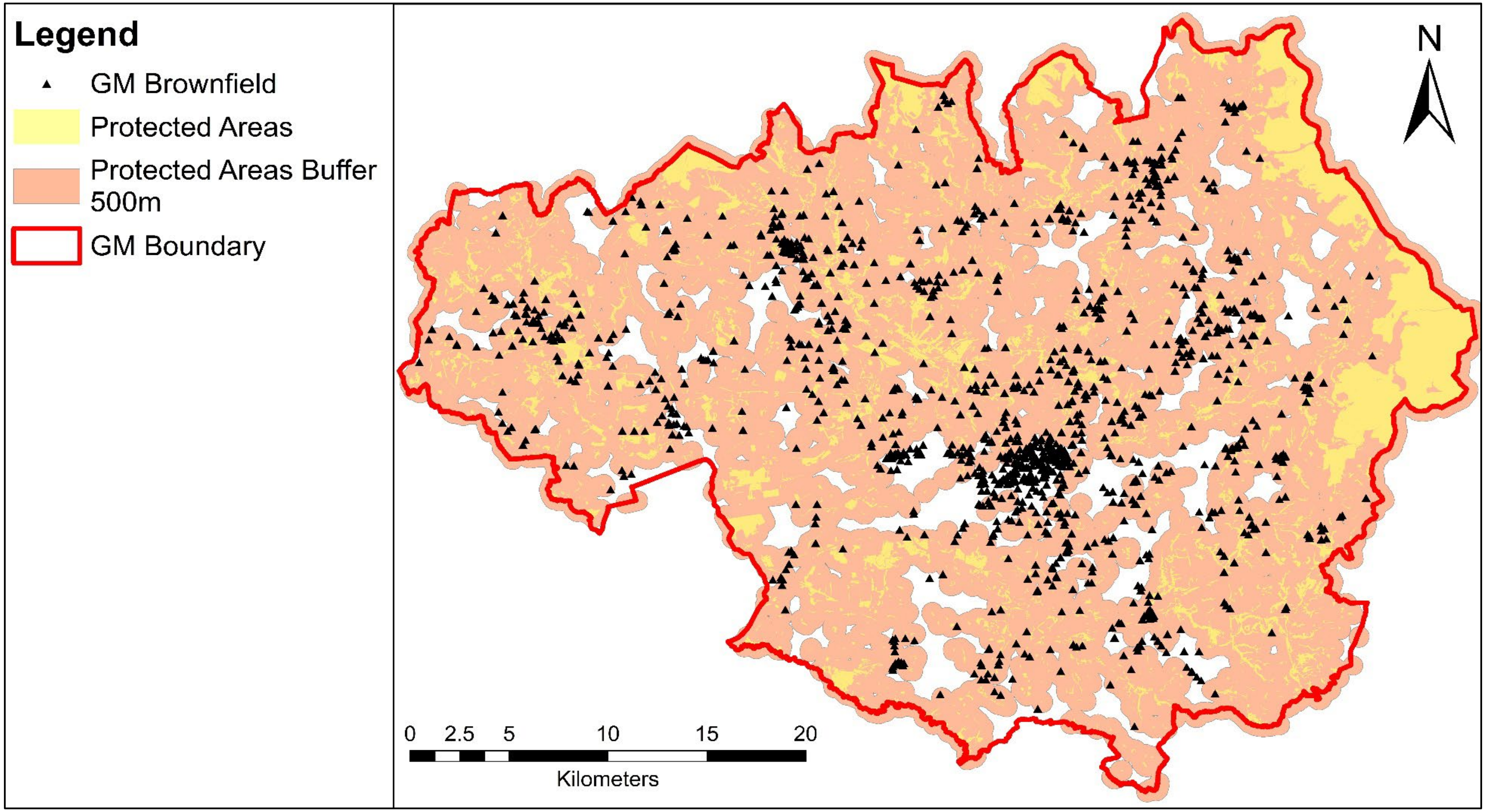
7.5.5 Protected Areas

Additional factors were included in the site consideration for WT to address aesthetic and environmental impacts posed by WTs. Recommended by DCLG (2015), the need for RE and low carbon technologies does not override environmental protections. As such, the designation of Special Protection Areas (SPA) published by Natural England was considered to protect wild birds that inhabit the woods, wetlands and water bodies including rivers, beaches and seas from WTs. In parallel, Important Bird Areas (IBA) were identified by the Royal Society for the Protection of Birds (RSPB), highlighting the conserved areas for broader bird habitats.

Special Areas of Conservation (SAC) was created under the European Directive for the Conservation of Natural Habitats and Wild Fauna and Flora (European Commission, 2020). These conservation areas were factored into this research. Some areas of SPA, IBA and SAC, particularly offshore, overlap with each other. However, most of the GM areas do not fall into these categories, except for the hilly areas in the east. These environmental components were considered in the site selection process to ensure that protected areas were excluded.

The extent of a buffer zone for SPA was not mentioned in the literature, so one value was used for all protected areas due to the overlapping with SAC in multiple areas. Additionally, Priority Habitats Inventory (PHI) was also factored in. This is because many habitats are protected under the environmental law and a development needs to be beyond a set buffer distance (Uyan, 2013; Tegou, et al., 2010).

All four types of environmental protection data were converted into spatial data and merged to produce a combined layer with a 500 m buffer zone, as implemented in Ramirez-Rosado et al. (2008), Yue & Wang (2006) and Tester et al. (2005). The same combination was performed by Watson & Hudson (2015) for the Site of Special Scientific Interest (SSSI), Special Areas of Conservation (SAC), Ramsar and Local Nature Reserve (LNR). Map 7.9 shows the combined protected areas and locations of brownfield sites.



Map 7.9: Combined protected areas of SPA, SAC, IBA and PHI in yellow and their buffer in dark orange (RSPB, 2017; Natural England, 2015).

7.5.6 Airport and Urban Areas

Most literature applied a buffer distance to residential areas to address the noise and safety concerns, with the smallest value of 350 m used by Barclay (2010). Airports should not be within a 2.5 km distance from wind farms (Aydin, et al., 2013; Nguyen, 2007; Voivontas, et al., 1998). The need for a large buffer zone between a wind farm and an airport is to prevent interference with the aviation radar system (Perry & Biss, 2007). WTs can also cause physical obstructions, adverse effects on the overall performance of communication, navigation and surveillance equipment and turbulence (Civil Aviation Authority, 2016). This caution was applied in this research for utility-scale WT installations.

To achieve the goal of this research to build sustainable cities, urban areas are inevitably the most advantageous locations to be developed due to their highest energy demand. Urban areas were not excluded from the site identification process to balance the supply and demand of energy in urban regions. Instead, brownfield sites with built infrastructure can still host urban WT if suitable facilities are installed. Types of installable urban WTs are explained in Chapter 2.

7.6 Ground Source Heat Pump Placement

For this research, all available brownfield sites were evaluated for underground heat harvesting. This means that the solar panel or WT placement does not have an impact on the GSHP installation. The heat collectors in the GSHP systems are loops of pipe buried in trenches or boreholes to absorb ground heat which is then transferred via pressured water for district heating. Both methods of laying closed-loop pipes were considered as brownfield sites are available in different sizes.

Regarding the economic factor, digging boreholes to place vertical loop pipes is costlier than digging shallow holes for flat-laid pipes or slinky coils (Busby, et al., 2009). The heat collector pipes must first be laid down in the ground to complete the GSHP installation before other RE technologies are placed. Table 7.12 outlines common parameters considered in a GSHP system in the literature.

Table 7.12: Criteria for GSHP installation.

Type	Variable	Value	Reference	Location
Trench	Depth	1-2 m	(GreenMatch, n.d.; GSHP Association, 2007)	UK
		1-1.5 m	(Energy Agency, 2018)	UK
		1.5-2 m	(Williams, 2013)	UK
		6 ft. (1.8 m)	(WePowr, 2016)	USA
	Length	50-80 m	(Centre for Alternative Technology, n.d.)	UK
		50-100 m	(Williams, 2013)	UK
		300 ft. (91 m)	(WePowr, 2016)	USA
	Pipe separation	0.9 m	(Williams, 2013)	UK
		3m	(GSHP Association, 2007)	UK
		5 m	(Centre for Alternative Technology, n.d.)	UK
Borehole	Depth	90 m	(Williams, 2013)	UK
		15-150 m	(GSHP Association, n.d.)	UK
		50-400 ft. (15-122 m)	(WePowr, 2016; GSHP Association, 2007)	USA, UK
		100-150 m	(Centre for Alternative Technology, n.d.; GreenMatch, n.d.)	UK
		100-250 m	(Energy Agency, 2018)	UK
	Length	20-50 m	(Centre for Alternative Technology, n.d.)	UK
	Pipe separation	10-20 ft. (3-6 m)	(WePowr, 2016)	USA
		7 m	(GSHP Association, 2007)	UK
		8 m	(Williams, 2013)	UK

7.6.1 Ground Size and Conditions

A well-insulated 25 m^2 living space requires 1 kW of heating and for every 1 kW of heat supplied, 10 m of horizontal piping is needed to harvest the ground heat (Cernunnos, 2016). However, Energy Agency (2018) provided a contrasting opinion that to supply 1 kW of heating, 20-30 m of horizontal trench is needed. If slinky coils are used, 10 m of coils are sufficient to supply the same amount of energy. To install horizontal pipes in trenches, a minimum of 0.5 acre of land is needed, which is around 0.202 hectare, or 2,023 m^2 (GreenMatch, n.d.), whereas 90m^2 was recommended by Williams (2013).

The analysis of bedrock geology is vital for the vertical-loop heat collectors in boreholes, whereas the superficial deposits are important for the horizontal heat collectors buried in trenches (Rosen & Koohi-Fayegh, 2017; Busby, et al., 2009; Busby, 2005; Gale, 2004). Bedrock forms the base of an area, which is commonly overlain by superficial deposits, landslide deposits or artificial deposits, in any combination.

Superficial deposits are relatively young geological deposits that lie on the bedrock in many areas (British Geological Survey, 2018). It is useful to analyse the ground type of a development area before digging. Analyses can include examining the thickness and nature of soil and bedrock by conducting a comprehensive geology and thermogeology. They are very useful as they can determine the excavation or drilling method necessary due to rock thickness and strength. Any associated costs can also be estimated (Busby, et al., 2009). Such analyses can also expose any hazardous ground conditions to the installer. A superficial thickness map is shown in Map 7.13.

The thermogeology influences the temperature gradient in the subsurface which indirectly affects the amount of heat absorbed by collector pipes. The thermal gradient can be obtained using an estimated thermal conductivity of the bedrock geology. Thermal conductivity is the rate at which heat passes through a specified material. It is measured in Watts per metre Kelvin (W/mK). It can vary by a factor of more than two for common rocks (1.5 W/mK to 3.5 W/mK), but can vary vastly for many superficial deposits. The main cause for this effect is the porosity (void within the soil) and water saturation (Busby, 2005). Ground temperatures are different depths are estimated as shown in Table 7.13.

As a comparison, granular soils with silt or clay have a higher conductivity than granular sandy soils. This is due to the lower porosity level in the soil that causes the heat to be transferred more easily. The moisture in packed soil also affects the level of conductivity as compared to dry loose soil which traps air (Omer, 2017; Ground Source Heat Pump Association, 2007). Thermal conductivity varies inversely with temperature but for GSHP applications, this variation is less important (Gale, 2004). The level of thermal conductivity for bedrocks and superficial deposits are charted in Figure 7.8.

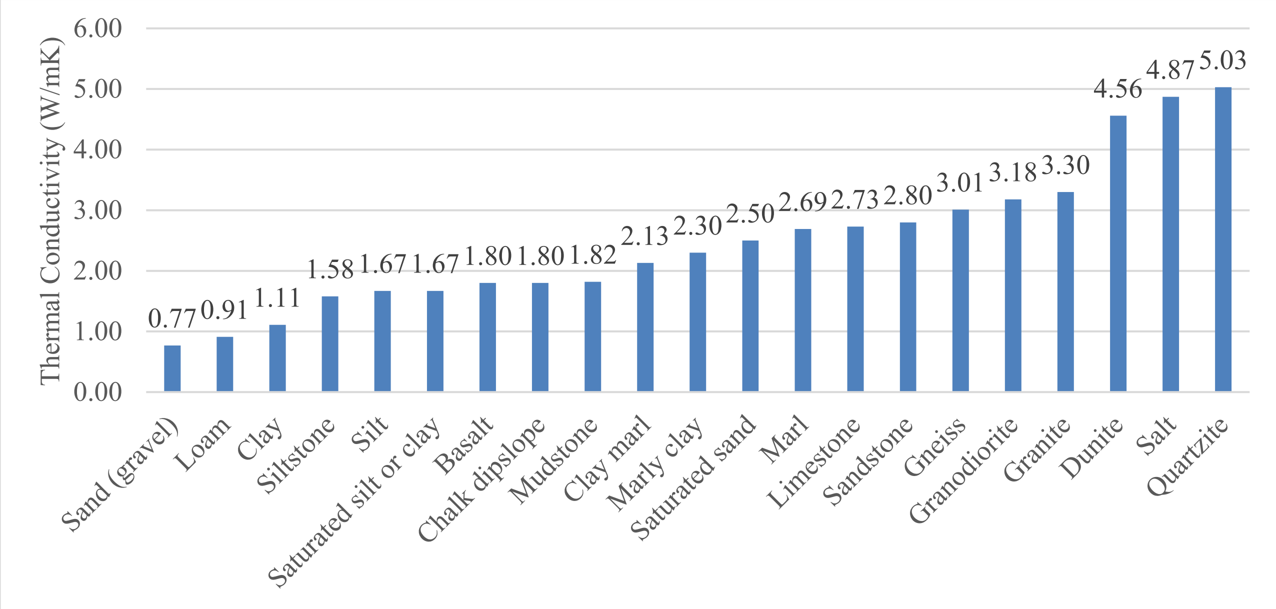


Figure 7.7: List of thermal conductivity for various bedrocks and superficial deposits (Busby, et al., 2009; Gale, 2004; Rollin, 2002).

Table 7.13: Estimated ground temperature at different depths (British Geological Survey, 2011).

Depth	Estimated temperature
50 m	12°C
100 m	13°C
150 m	13.9°C
200 m	14.8°C

Due to the nature of complex bedrock and superficial geology in the UK (shown in Map 7.11 and Map 7.12), it is not possible to have a universal design rule for open-loop systems and closed-loop systems. There needs to be site-specific analyses instead, applying local information in the system design process. It includes a thermal response test (TRT) that provides the most accurate estimate of a site's thermal properties (Busby, et al., 2009; Banks, 2008).

TRT is crucial as a reference and studied data only provide for a broad range of values, but with an in-depth test, the accuracy can be increased by up to ±10%. By conducting the test, system failure and unnecessary costs can be reduced. The TRT involves drilling a test borehole, installing a U-tube, flushing it, filling it with fluid and leaving it for several days. It is recommended to leave it for 50 hours or longer. The initial temperature is measured before it is put on a heat flux. Parameters that can be measured during the process include flow and return temperatures, flow rate, power input and ambient temperature (Rees, 2011). The result is an estimate of local ground thermal conductivity with a high accuracy.

Apart from bedrock, superficial deposits also influence the suitability for GSHP installations. The thermal conductivity of superficial deposits depends on the nature of the deposit, bulk porosity and degree of saturation. These characteristics can be estimated by classifying soils according to their particle size and composition (British Geological Survey, 2011). As a guide, deposits with silt or clay have higher thermal conductivities than clean granular sands. However, clean sands have a higher conductivity when damp or saturated.

To study superficial conductivities for GSHP installations, soil textures were studied. Figure 7.9 illustrates the soil textures according to their mix and Map 7.13 shows the soil textures for GM, illustrating a majority of loam to clayey loam coverage which indicates many sites having a high thermal conductivity. Besides providing an estimate of the system efficiency, the digging process/procedure for trench collectors installation can also be identified.

Based on the soil texture mix superficial deposits maps (Map 7.12 and Map 7.13), and the availability of the thermal conductivity data for only individual type of deposits and bedrocks (Figure 7.8), the site identification for this research was conducted using only the available thermal conductivity data for bedrocks. An estimate by combining individual values was not performed to avoid miscalculation and data fabrication.

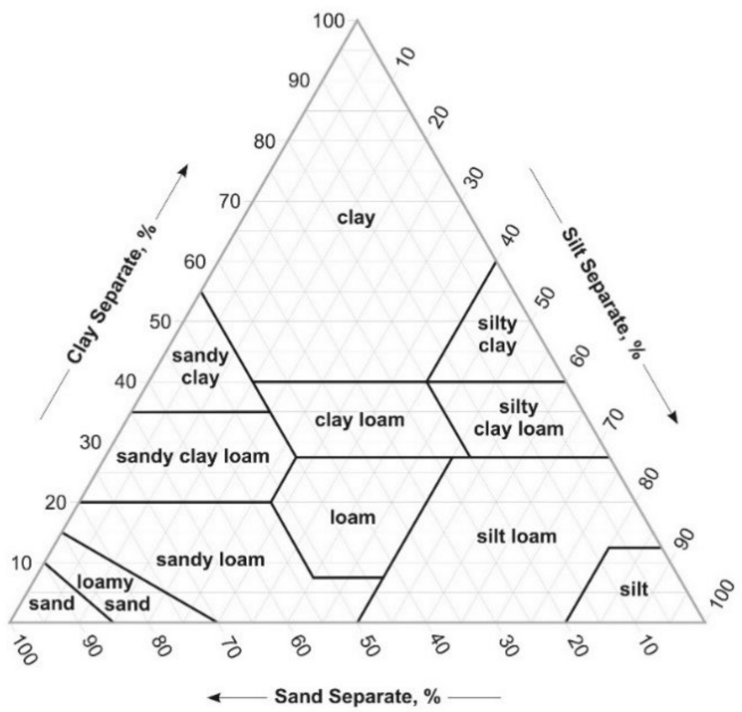
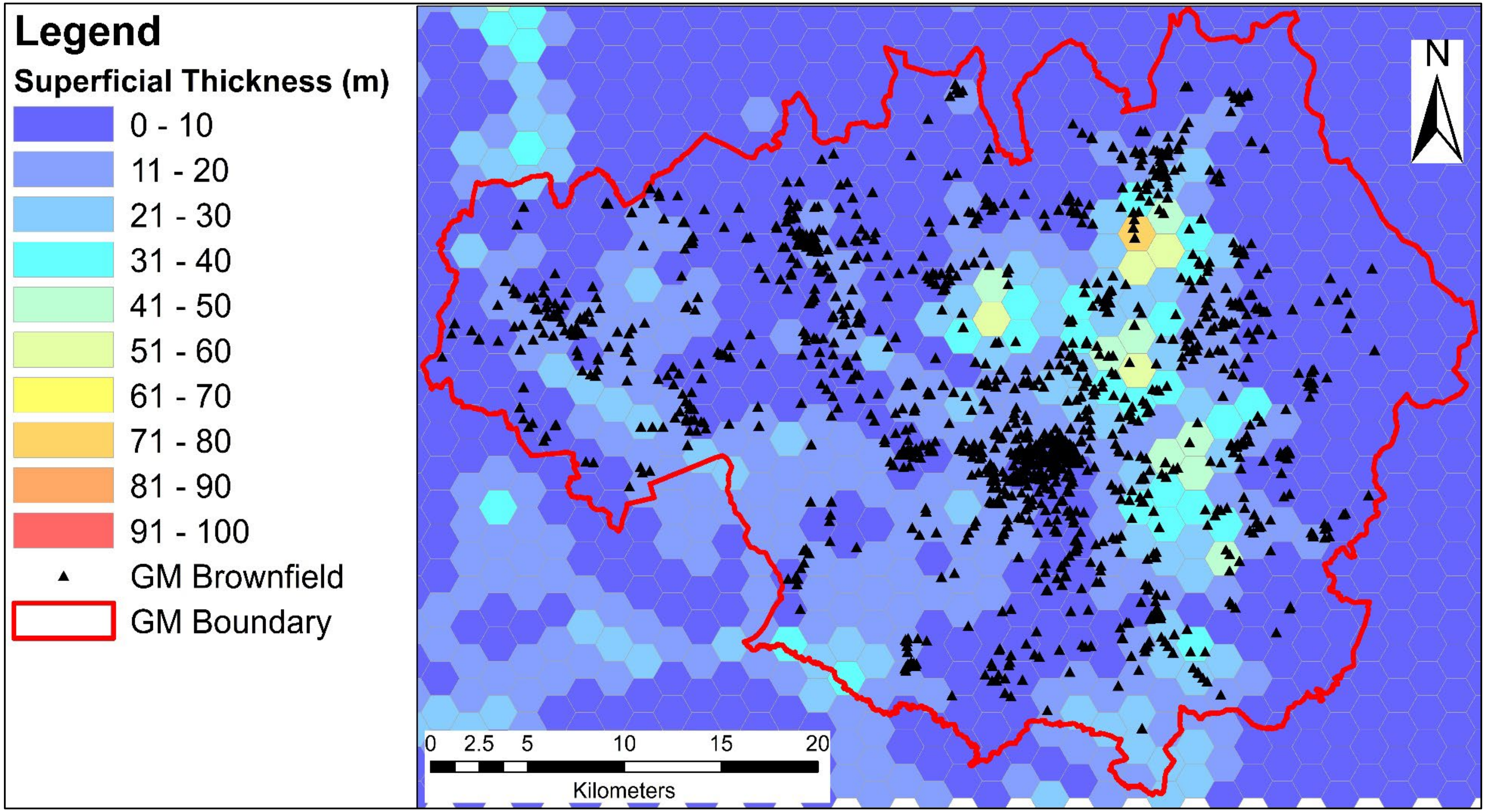
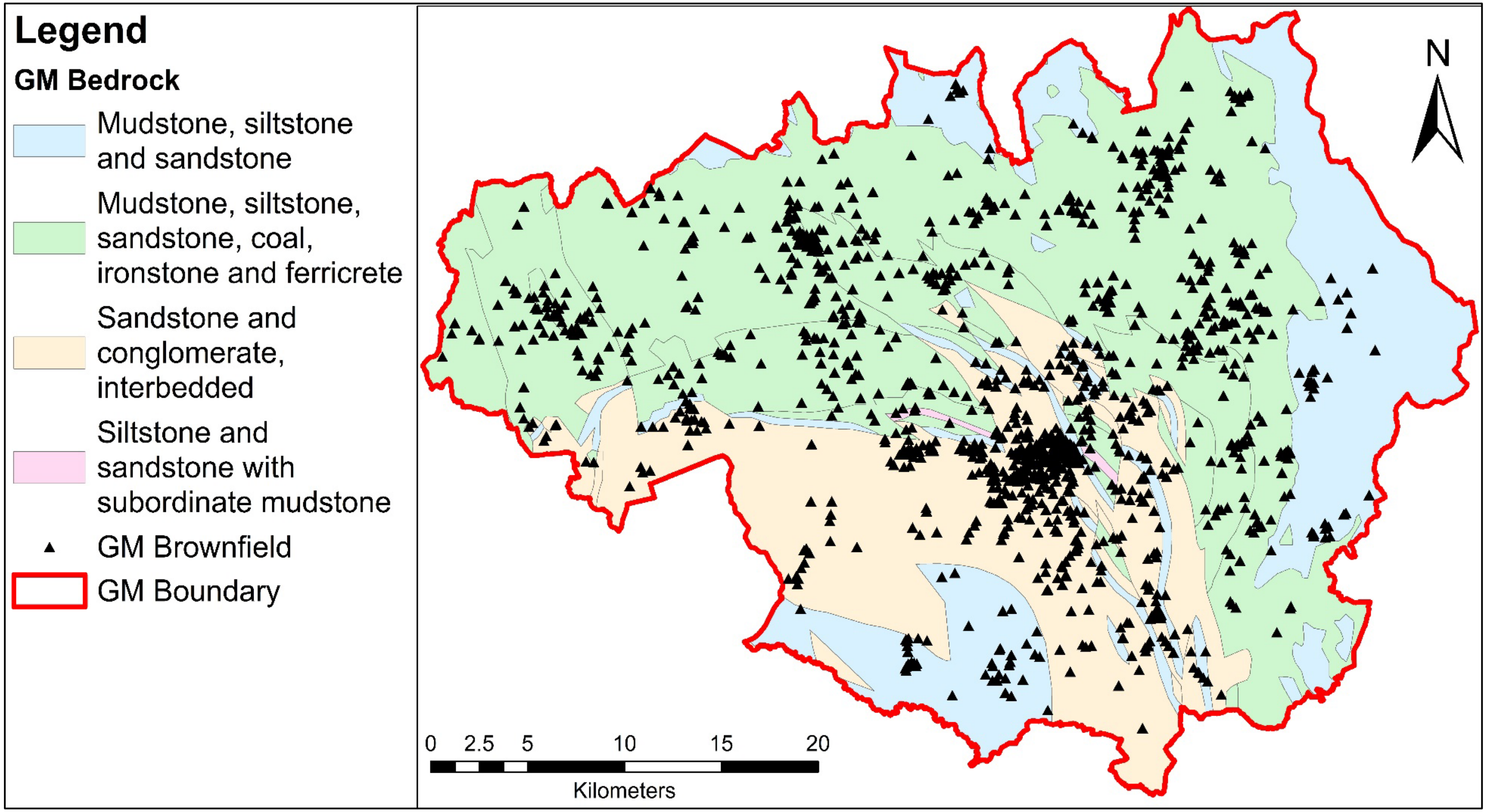


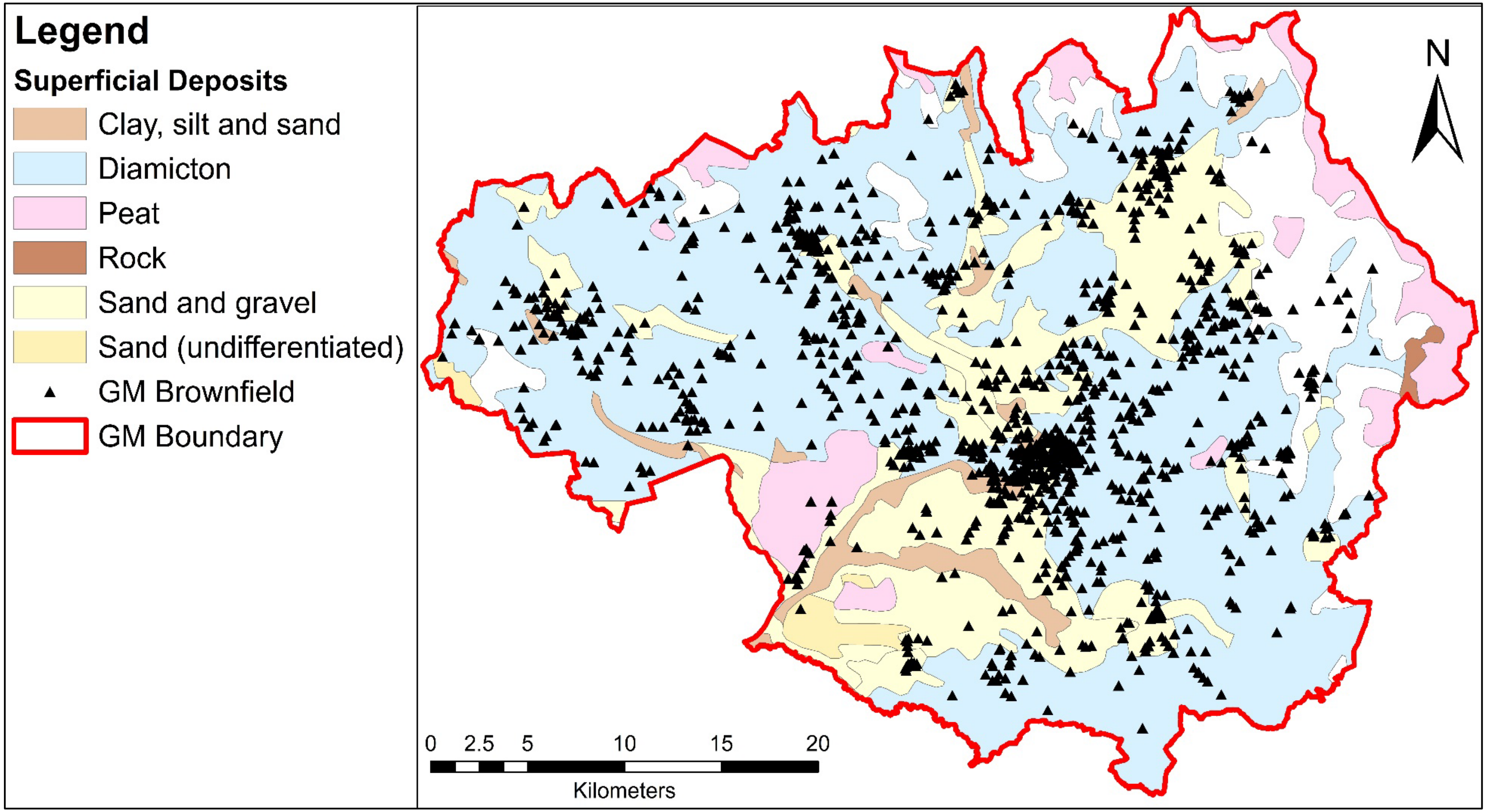
Figure 7.8: Soil texture triangle (USDA, n.d.).



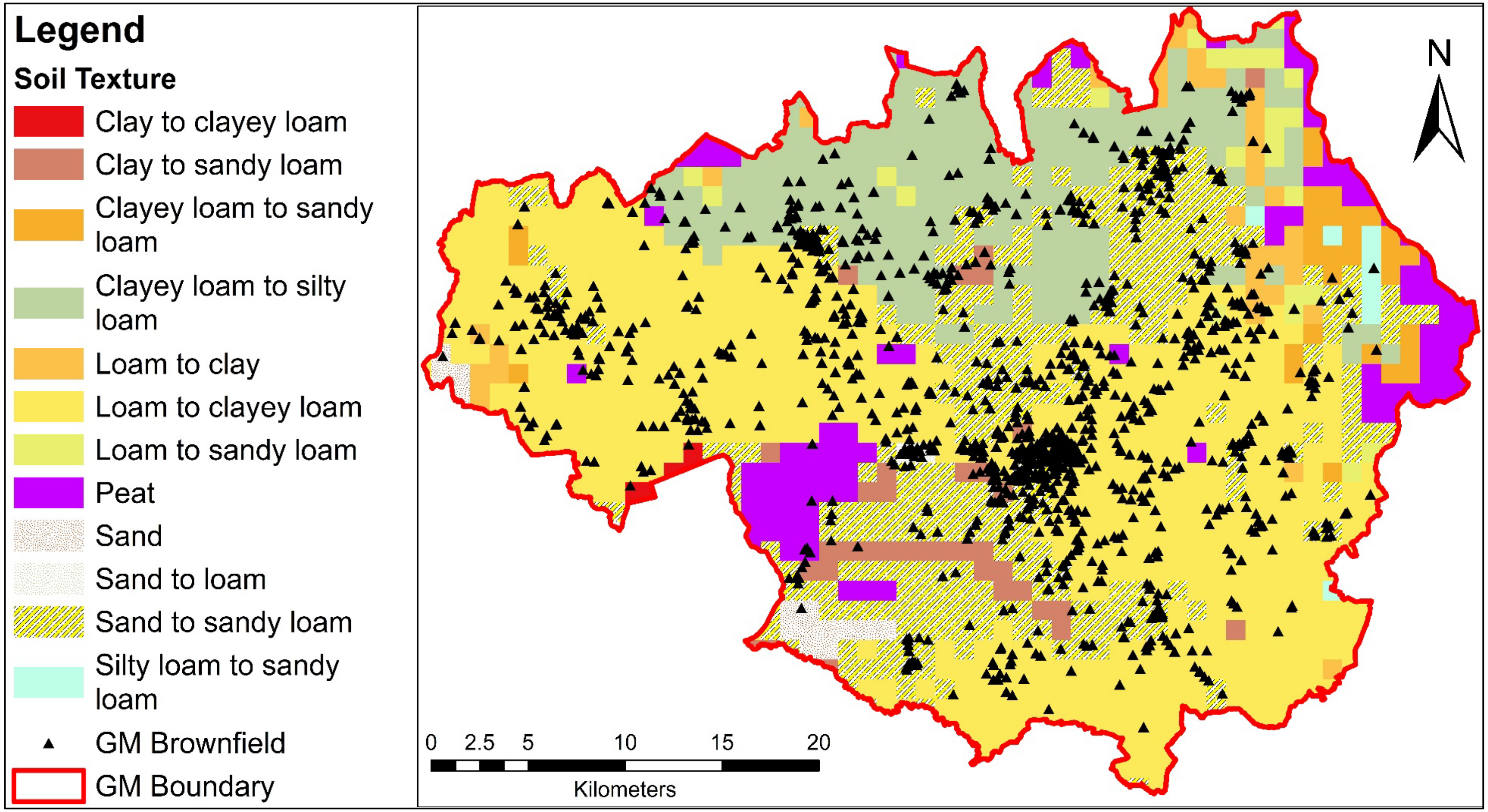
Map 7.10: Most of the GM region is covered by superficial deposits of 0 to 30 m thickness (British Geological Survey, 2008).



Map 7.11: Bedrock throughout GM region. Most of the area has mudstone, siltstone, sandstone, coal, ironstone and ferricrete as the bedrock (British Geological Survey, 2008).



Map 7.12: The majority of superficial deposit in GM is diamicton, followed by sand and gravel (British Geological Survey, 2008).



Map 7.13: Primary soil texture in GM is made up of loam to clayey loam (British Geological Survey, 2019).

7.6.2 Urban Areas

Denser areas are recommended for the installation of district heating systems to increase the system efficiency and optimise the investment cost (Heat Roadmap Europe, 2018). The denser areas correspond to more developed areas of Manchester and Salford, followed by Stockport and other sub-urban areas. Only two areas are covered by district heating systems at the time of writing; Media City in Salford and St. Mary's in Oldham (Energy Technologies Institute, 2016).

The energy demand in the whole GM is 51.6 TWh/year, where 42% of the energy demand is for heating and only 23% is for electricity (Energy Technologies Institute, 2016). This is equivalent to 21.67 TWh of heating. The highest heat demand is in Manchester due to its higher population density that includes residences, businesses and industry (Heat Roadmap Europe, 2018). Shown in Map 7.14, the population in Manchester is the highest with 11,070 of residents/km^2 (Reis, et al., 2017).

In such a high-density area, district heating implementations incorporating brownfield-based GSHP should be prioritised since they can provide supplementary heat for the neighbouring areas more efficiently. Proximity to higher density areas was taken into account in prioritising brownfield sites to be developed together with other criteria. Population density in GM was divided into 10 classes in a linear pattern, shown in Table 7.14.

Table 7.14: Classification of population density.

Classification used	Population density (per km$^{2)}$	Assigned rating
10	9,963 – 11,070	1.0
9	8,856 – 9,963	0.9
8	7,749 – 8,856	0.8
7	6,642 – 7,749	0.7
6	5,535 – 6,642	0.6
5	4,428 – 5,535	0.5
4	3,321 – 4,428	0.4
3	2,214 – 3,321	0.3
2	1,107 – 2,214	0.2
1	0 – 1,107	0.1

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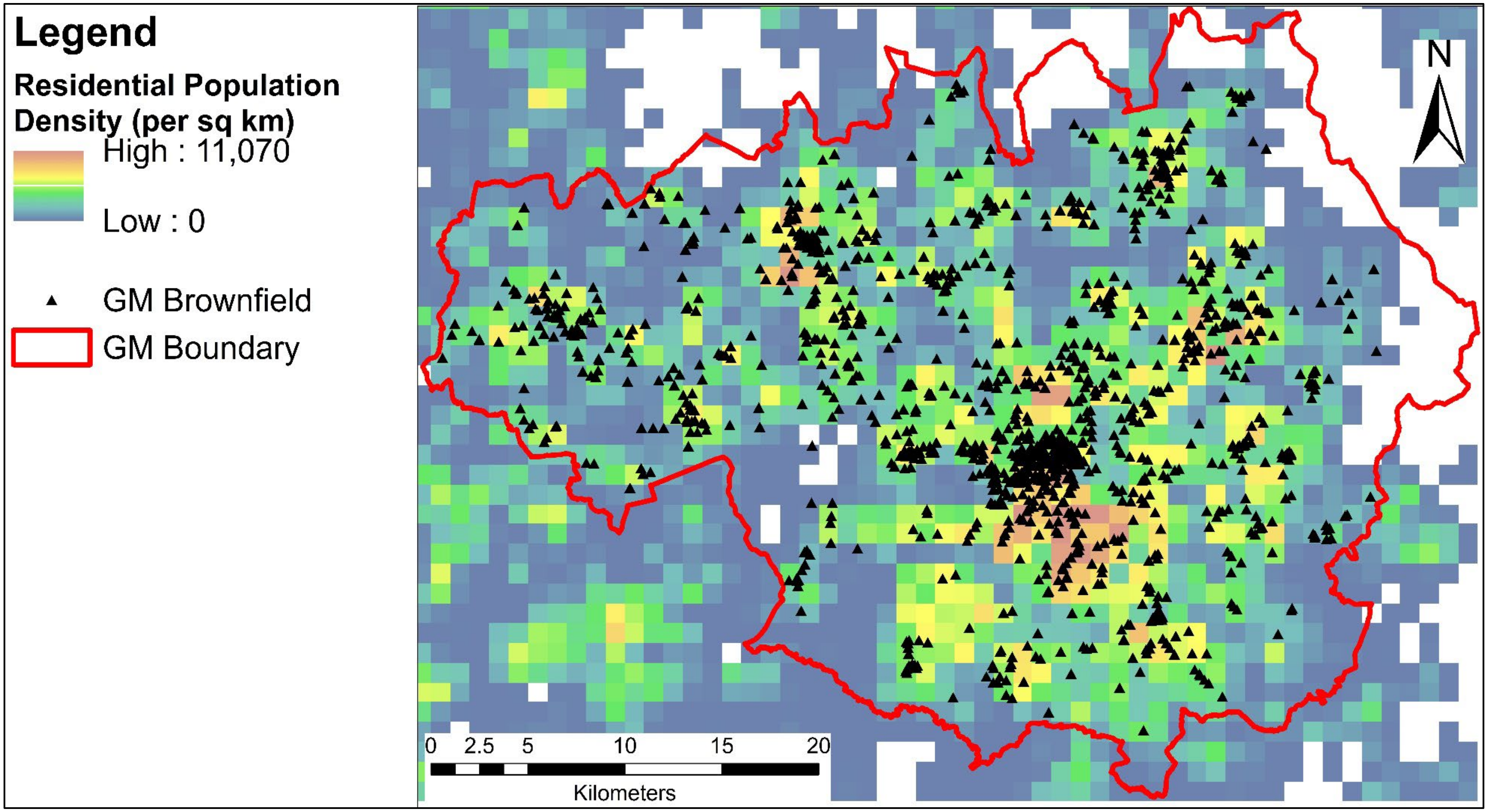


Map 7.14: GM brownfield sites with a high concentration in higher density areas (Reis, et al., 2017).

7.7 Summary

Chapter 7 focused on the criteria applied in research to identify suitable sites for solar PV and WT in detail to select relevant criteria for the GM study. Some research considered similar criteria for solar PV and WT installations, for instance, urban areas, distance to substations and distance to roads. Nevertheless, not all criteria were applied in this research; only those appropriate for GM brownfield conditions were adopted.

Criteria were classed as ‘restriction’, where values outside an acceptable range were excluded, or as ‘evaluation’, where rating systems were used for all the available values within the criteria. For solar PV, the only restriction criterion was aspect, while site size, solar radiation and flood zone were classed as evaluation. For WT, airport areas and protected areas (which comprised of Priority Habitats Inventory, Important Bird Areas, Special Areas of Conservation and Special Protection Areas) were excluded from potential WT siting. Site size, slope and wind speed were categorised as evaluation and were rated. Using the rating specified in respective sections in this chapter, the selected criteria were applied in the spatial analysis process using ModelBuilder. The complete process is explained in Chapter 8.

To identify suitable sites for GSHP, appropriate technicalities of good heat pumps were reviewed in this chapter, including ground size needed and suitable soil conditions. Loam to clayey loam was concluded to have a higher thermal conductivity than silt and sand. It has higher and quicker heat exchange between the soil and the fluid in the collector. The population density was also assessed and considered as a criterion for GSHP site selection. Chapter 8 follows with the workshop results and how they were used in the spatial analysis to identify suitable sites, incorporating the criteria elaborated in this chapter.

Chapter 8 : Criteria Weightings and the Stages of GIS Analysis

8.1 Introduction

This chapter begins by adopting weightings used in similar contexts for both solar PV and WT to address the fourth research objective which is to undertake a spatial analysis using GIS to identify suitable brownfield sites for development. The chapter then discusses the results from the pilot and MCDM workshops before applying them in the GIS analysis. The results are compared in terms of their differences using various AHP weighting scales.

Later on, three scenarios are examined as a sensitivity analysis. This shows where stakeholders/decision makers prefer different criteria over the other. The weightings deduced from previous studies, obtained from experts in the MCDM workshop and sensitivity analysis weightings are compared in terms of their weighting distribution. Stages of spatial analysis applied in GIS are then explained and how ModelBuilder is utilised as part of the process. The site identification process for GSHP is also outlined.

8.2 Criteria Weightings Deduced from the Literature

To obtain criteria weightings, three steps were performed in AHP: 1) criteria comparison and matrix formation; 2) criteria normalisation; and 3) consistency check. The relative importance of one criterion to another was adopted from similar comparisons in the literature. Various literatures use different relative importance when comparing criteria priorities in their project, which yield a set of different final weightings. This is influenced by the number of criteria considered, as well as how one criterion is preferred over another.

This section aims to derive criteria preference/weightings used in previous solar PV and WT installations in the literature by considering the nature of the criteria and their quantity. This forms the basis of AHP usage in determining criteria weightings and a guide to the process.

8.2.1 AHP Step 1: Criteria Comparison for Solar PV

The first step of the AHP process compares two independent criteria in pairs in terms of their importance to a particular project. For this research, solar radiation was compared to flood zone before it was compared to site size. As the two latter criteria were selected specifically for the GM context, there was no other research that used such a comparison before. But deducing from their highest weighting of solar radiation when compared to other criteria (for example, in Al-Garni & Awasthi

(2017), Georgiou & Skarlatos (2016) and Carrión et al. (2008)), the same principle was adopted in this research. Therefore, to set the solar radiation as the highest-ranking criterion followed by the other two, the following AHP comparison in Table 8.1 was established.

Table 8.1: Pairwise comparison for solar farm criteria..

Criteria	Solar radiation	Flood zone	Site size
Solar radiation	1.00	9.00	7.00
Flood zone	0.11	1.00	0.33
Site size	0.14	3.00	1.00
Column Sum	**1.25**	**13.00**	**8.33**

Once all the criteria were compared, the sum of values in each column was computed. This was for the next step: criteria normalisation. In many quantitative analyses that involve data from various sources, a standardisation process is essential to ensure a meaningful comparison of criteria measured on different scales (Carver, 1991). The decision matrix was then converted into normalised criteria weightings using Step 2.

8.2.2 AHP Step 2: Criteria Normalisation for Solar PV

A normalised scale is needed when different criteria measured in different units are used, for example, solar radiation in kWh/m^2/day and flood zone in discrete numbers. To obtain the normalised criteria following the pairwise comparison, each criterion in the criteria column was normalised from their initial value in Table 8.1 by using equation (8-1) (Saaty, 1980). The results are obtained as in Table 8.2:

$$\bar{x} = \frac{Comparison\ x_{ij}}{Column\ Sum\ in\ the\ respective\ column} \quad (8\text{-}1)$$

Table 8.2: Normalised criteria values and their final weightings

	Solar radiation	Flood zone	Site size	Row sum	Average score	Weighting %
Solar radiation	0.80	0.69	0.84	2.33	0.78	77.66
Flood zone	0.09	0.08	0.04	0.21	0.07	6.85
Site size	0.11	0.23	0.12	0.46	0.15	15.49
Total	**1.00**	**1.00**	**1.00**	**3.00**	**1.00**	**100.00**

To obtain the Solar radiation vs Solar radiation value (0.80) in Table 8.2, the value of Solar radiation in the first row in Table 8.1 (1.00) was divided by the Column Sum of Solar radiation (1.25). This means, for Solar radiation vs Solar radiation (Table 8.2),

$$\bar{x}_{SR,SR} = \frac{\text{Solar radiation vs Solar radiation (Table 8.1)}}{\text{Column Sum of Solar radiation (Table 8.1)}} = \frac{1.00}{1.25} = 0.8$$

The same method was performed for Solar radiation vs Flood zone, where 9.00 was divided by 13.00 (in Table 8.1) to get 0.69 (in Table 8.2);

$$\bar{x}_{SR,FZ} = \frac{\text{Solar radiation vs Flood zone (Table 8.1)}}{\text{Column Sum of Flood zone (Table 8.1)}} = \frac{9.00}{13.00} = 0.69$$

To obtain other values to complete the Table 8.2, equation (8-1) was used.

The sum of normalised criteria values (in the column) equals to 1, due to the values representing a percentage of the criteria, shown as the Total. The Average score was then computed by summing the row values and dividing by the number of criteria. For Solar radiation (Table 8.2),

$$SR_{avg} = \frac{0.80 + 0.69 + 0.84}{3} = 0.78$$

The Average score was computed for the remaining criteria before they are transformed into weightings in per cent. This was done by multiplying the Average score by 100. The weightings of 77.66%, 6.85% and 15.49% were obtained as illustrated in Table 8.2.

8.2.3 AHP Step 3: Consistency Check for Solar PV

The final step of the AHP method is the consistency check, contrary to other MCDM methods where the criteria ranking or weighting is the last step. This step provides a way of checking whether the pairwise comparison values in Table 8.1 are consistent or not. Due to manual human judgement in setting relative pairwise comparison in AHP, different values can yield different results/weightings. Certain sets of values can mean inconsistent judgement, it is important to run this final step before applying the weightings obtained in Table 8.2 to the site identification.

To execute the consistency check, the eigenvector for each matrix was calculated by using matrix multiplication. This was computed for each Criteria row in Table 8.1 with the value in the Average score column in Table 8.2. They were then divided by the respective criterion's average score. For instance,

$$\text{Eigenvector of Flood zone} = \frac{[\text{Row values in Table 8.1}] \times [\text{Average score values in Table 8.2}]}{\text{Average score for Flood zone}} \quad (8\text{-}2)$$

$$= [0.11 \quad 1.00 \quad 0.33] \times \begin{bmatrix} 0.78 \\ 0.07 \\ 0.15 \end{bmatrix} \div 0.07 = 3.01$$

To obtain the Consistency Index (CI) value, equation (8-4) was used, where λ_{max} means the Average consistency, indicated by the sum of all eigenvectors divided by the number of criteria. In this case,

$$\lambda_{max} = \frac{3.19 + 3.01 + 3.04}{3} = 3.08 \quad (8\text{-}3)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{3.08 - 3}{3 - 1} = 0.04 \quad (8\text{-}4)$$

The calculation of Consistency Ratio (CR) followed using equation (8-5), applying the Random Index (RI) value in Table 8.3. The RI value used in this instance was 0.58 to reflect the number of criteria used, which was 3.

$$CR = \frac{CI}{RI} = \frac{0.04}{0.58} = 0.07 \quad (8\text{-}5)$$

Table 8.3:Random index for n=1 to n=10.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

The values for all criteria eigenvectors, average consistency, CI and RI are shown in Table 8.4:

Table 8.4: Consistency check parameters for solar PV siting.

Solar radiation	3.19
Flood zone	3.01
Site size	3.04
Sum	**9.24**

No. of criteria (n)	3
Average consistency (λ*max*) (Sum/no. of criteria)	3.08
Consistency Index (CI)	0.04
Random Index (RI)	0.58
Consistency Ratio (CI/RI)	0.07

The resulting CR from the computation was 0.07, which was lower than 0.1. Hence, it indicated the validity of the weightings obtained in Table 8.2. The weightings 77.66% for solar radiation, 6.85%

for flood zone and 15.49% for site size (Table 8.5) were used in the spatial analysis elaborated in section 8.6.

Table 8.5: Weightings deduced from Al-Garni & Awasthi (2017), Georgiou & Skarlatos (2016) and Carrión et al. (2008) for solar PV.

Solar Radiation	Flood Zone	Site Size
77.66%	6.85%	15.49%

8.2.4 AHP Step 1: Criteria Comparison for Wind Turbine

The same process was repeated to determine the weightings of criteria for WT. Where wind speed was compared with other criteria in the literature (Ayodele, et al., 2018; Latinopoulos & Kechagia, 2015; Neufville, 2013; Tegou, et al., 2010), the highest value used in the pairwise comparison was 7 (based on Saaty's scale), hence 7 was adopted in this research when comparing to slope and 5 was assigned to the comparison with site size. The pairwise matrix is shown in Table 8.6.

Table 8.6: Pairwise comparison for wind energy criteria.

Criteria	Wind speed	Slope	Site size
Wind speed	1.00	7.00	5.00
Slope	0.14	1.00	0.33
Site size	0.20	3.00	1.00
Column Sum	**1.34**	**11.00**	**6.33**

Normalised criteria values were computed for each criterion to yield their final weightings using similar steps for solar PV and equation (8-1) once the pairwise comparison matrix was formed.

8.2.5 AHP Step 2: Criteria Normalisation for Wind Turbine

A similar method of normalisation was performed for WT as for the solar PV identification. Table 8.7 shows the weighting corresponding to the level of importance for wind speed which is significantly higher than slope and site size. Considering that the site size is more important to generate more energy compared to the slope which can be altered, this section considered the lowest importance/weighting for the slope criterion. The completed table was then evaluated for the consistency of judgement.

Table 8.7: Normalised criteria values and final weightings.

	Wind speed	Slope	Site size	Row sum	Average Score	Weighting %
Wind speed	0.74	0.64	0.79	2.17	0.72	72.35
Slope	0.11	0.09	0.05	0.25	0.08	8.33
Site size	0.15	0.27	0.16	0.58	0.19	19.32
Total	**1.00**	**1.00**	**1.00**	**3.00**	**1.00**	**100.00**

8.2.6 AHP Step 3: Consistency Check for Wind Turbine

Performing the same steps as the earlier Consistency Check for Solar PV, the results obtained for the consistency check based on Table 8.7 are simplified in Table 8.8.

Table 8.8: Consistency check parameters for WT siting.

Wind speed	3.14
Slope	3.02
Site size	3.04
Sum	**9.20**

No of criteria (n)	3
Average consistency (λmax)	3.07
Consistency Index (CI)	0.03
Random Index (RI)	0.58
Consistency Ratio (CI/RI)	0.06

Applying the weightings of 72.35%, 19.32% and 8.33% for wind speed, site size and slope (Table 8.9), all the criteria layers were combined using ArcGIS' ModelBuilder to produce the evaluation layer discussed in section 8.7.

Table 8.9: Weightings deduced from Ayodele et al. (2018), Latinopoulos & Kechagia (2015), Neufville (2013) and Tegou et al. (2010) for WT.

Wind Speed	Site Size	Slope
72.35%	19.32%	8.33%

8.3 Criteria Weightings and Responses from Pilot Workshop

The AHP results of the pilot workshop were compared using different scales to observe any differences. Different scales produced different weightings for the same criteria, nevertheless, their sequence remained the same. The pilot workshop results showed that the highest group consensus was achieved using the Inverse Linear scale, followed by the Balanced scale. This was the case for both solar PV and WT. Hence, the Inverse Linear scale was used in the MCDM workshop as the final and prime scale to obtain the criteria weightings for both technologies.

In addition to weighting the criteria, a set of questionnaires were asked during the pilot workshop, as explained in Chapter 6. For the questionnaire, respondents' answers were recorded using the Select Survey. Running a pilot helped determine the feasibility of a workshop, the utilisation of AHP-OS and the questions to be asked. As the pilot workshop was run with results that could be applied in GIS analysis, the MCDM workshop was conducted in the same manner.

8.4 Criteria Weightings and Responses from MCDM Workshop

The same session flow was repeated for the final MCDM workshop with similar questions asked, probing their knowledge on the importance of criteria and technology to be installed. The AHP comparison results for solar PV obtained from the participants are tabulated in Table 8.10. The results illustrate for all the scales available in the software, as explained in section 6.7.

Table 8.10: AHP weightings from MCDM workshop for solar PV.

Scale	Solar Radiation	Site Size	Flood Zone	CR	Group consensus
Linear AHP Scale	57.7%	28.2%	14.1%	0.0%	66.8%
Log Scale	48.7%	31.1%	20.0%	0.1%	67.9%
Root Square Scale	45.6%	31.9%	22.6%	0.0%	70.2%
Inverse Linear Scale	39.4%	32.9%	27.6%	0.3%	83.8%
Balanced Scale	43.0%	32.4%	24.6%	0.5%	79.3%
Balanced-n Scale	45.3%	31.9%	22.8%	0.5%	76.6%
Adaptive Balanced Scale	47.3%	31.5%	21.2%	0.7%	75.0%
Adaptive Scale	64.6%	25.2%	10.2%	0.1%	63.3%
Power Scale	77.0%	18.4%	4.6%	0.1%	56.6%
Geometric Scale	65.1%	25.0%	9.9%	4.6%	56.1%

The weightings resulting from the MCDM workshop for the wind speed, site size and slope criteria are tabulated in Table 8.11.

Table 8.11: AHP weightings from MCDM workshop for WT.

Scale	Wind Speed	Site Size	Slope	CR	Group Consensus
Linear AHP Scale	66.2%	21.1%	12.6%	0.3%	82.2%
Log Scale	53.5%	27.0%	19.5%	0.4%	82.5%
Root Square Scale	50.0%	28.2%	21.8%	0.1%	83.2%
Inverse Linear Scale	43.6%	30.4%	26.0%	0.5%	85.3%
Balanced Scale	48.9%	28.4%	22.7%	0.6%	84.7%
Balanced-n Scale	52.1%	27.1%	20.7%	0.5%	84.2%
Adaptive Balanced Scale	55.3%	25.8%	18.8%	0.7%	82.9%
Adaptive Scale	74.9%	16.7%	8.5%	0.5%	80.9%
Power Scale	87.9%	8.9%	3.2%	1.2%	78.3%
Geometric Scale	80.5%	13.2%	6.3%	4.6%	76.6%

The different scales are named after the formula that they adopt and can take in different maximum number of criteria, with the smallest being the Logarithmic and Root square scales, with a maximum number of 4 criteria, and the biggest the Geometric scale with 257 criteria. The equations used and criteria number accepted are further explained in Appendix E. In different applications, different scales might be preferred due to the possibility to compute a large number of criteria for consideration. For example, when considering 50 criteria, using Logarithmic or Inverse Linear scales would not be possible as those scales are only able to consider up to 4 and 10 criteria respectively. Thus, Power or Geometric scales would be chosen.

The weighting distribution, consistency ratio (CR) and group consensus also play a role in determining which scale is best to use. Some scales have a smaller weight dispersion indicated by the small difference between the higher- and the lower- weighted criteria, while others have a bigger difference. By concept, the Balanced-n scale has no weight dispersion, which means that weightings are equally distributed over the judgement range (Goepel, 2019). The different scales also influence the CR and the group consensus values differently.

From Table 8.10 and Table 8.11, as the Inverse Linear and Balanced scales provide the weightings with the lowest weight dispersion and highest group consensus from the workshop results, these two scales are compared in this research. The results using the Inverse Linear scale (highlighted in green) have the lowest weight dispersion but the highest group consensus for both solar PV and WT cases, although in a guide by Goepel (2019), they mentioned that the Balanced-n scale and the Adaptive Balanced scale showed the best results. The second highest group consensus is produced by using the Balanced scale (in beige).

The weighting distribution, CR and group consensus also play a role in determining which scale is best to use. As the Inverse Linear and Balanced scales provide the weightings with the lowest weight dispersion and the highest group consensus from the workshop results, these two scales are compared in this research. The weightings from these scales are also compared in the spatial analysis in Chapter 9 to observe the effect of the scale to site priorities. Goepel (2019) noted that the Log and Root Square scales can lower the CR, whereas the Power, Geometric, Adaptive and Adaptive Balanced scales increase the CR.

The weightings using the Inverse Linear scale obtained from the MCDM workshop were applied in the evaluation model (elaborated in sections 8.6 and 8.7). Besides rating the criteria, a set of questionnaires were also distributed to participants. The questions resembled the ones used in the pilot workshop. For the question "why do you rate the criteria importance in such a way?", participants' responses varied. Most of them justified the assignment of solar radiation and wind speed the highest importance as they were the 'fuel factor' for the farms and they contributed directly to the energy output. Others thought that the solar radiation level was not highly deviated so it was less important to consider it as a factor instead of site size. Contrarily, wind speed had a higher variation and WT could work in isolation, so it was more important to consider than site size.

Alternatively, some participants thought that site size was the most important criterion, this was based on the theory that the renewable technology output is proportional to site size. Regarding the flood zone, sites located in the flood zone will not usually be developed to ensure infrastructure resilience and continuous supply of electricity. However, if they were to be developed, preventative measures would be taken to protect them from damage. There was also an opinion that only a small number of sites were in the flood zone. Hence, the lowest importance was assigned to flood zone.

Due to the potential of floods that can damage solar panels and associated electronics, participants had varied opinions. Many thought that it was not important to avoid flood areas in selecting sites, so they assigned flood zone a lower importance. For WT installations, the slope was perceived as the least important criterion due to most GM areas are flat, therefore flat sites could easily be prioritised in the selection.

For the final question "what other criteria do you think should also be considered?", participants' opinions were mostly criteria that were excluded from this research, including land value, distance to population centres, size of demand and surrounding temperature for solar PV installation. There were also suggestions to consider the cost of development, wind tunnel and wake recovery for WT and wind direction, but those factors were out of the scope of this research and could be used for site-specific analysis. A list of responses for both questions is provided in Appendix G.

8.5 Sensitivity Analysis

The initial steps explained in sections 8.2.1 to 8.2.6 were performed to extract weightings applied in the literature which allowed for the best results due to their preferred pairwise comparisons. The MCDM workshop was then run to obtain weightings from experts based on their subjective judgements for the GM context as no direct weighting could be adopted from literature, as discussed in section 8.4. To further simulate different stakeholders'/decision makers' preferences of selection criteria in different circumstances other than the decisions deduced from the literature or made by experts, a sensitivity analysis was performed. This was executed by applying different weightings in the AHP process for both solar and wind sites. This process, however, was not performed for the GSHP site identification as there were only two criteria involved.

A site priority system was achieved resulting from the application of different AHP weightings to produce layer overlay in GIS. Executing this method in real planning projects allows for a combination of GIS with MCDM techniques to occur, as suggested by Higgs et al. (2008). A sensitivity analysis can be executed by using different MCDM techniques or different weightings with the same technique as the initial analysis (Higgs, 2006; Carver, 1999). The results can reflect how changes to the weightings or methods used affect the final outputs, which can provide imminent signs that demonstrate the robustness of the model (Wu, et al., 2018). This is apparent when the weightings are altered to echo the changes that can affect the importance and selection of criteria, for instance, in the legal and planning framework, technological innovation changes, investments and society (Díaz-Cuevas, 2018).

For solar site identification, three scenarios were built to test results using different weightings defined by the user. The first scenario explored the prioritisation of brownfield sites when a higher weighting was assigned to site size than using weightings deduced from the literature. Comparing with the weightings using the Inverse Linear scale, Scenario 1 weightings are lower for site size and flood zone, but higher for solar radiation. This scenario assigned a 19.32% weighting for site size (3.83% higher than deduced weightings from Al-Garni & Awasthi (2017), Georgiou & Skarlatos (2016) and Carrión et al. (2008) and 13.58% lower than workshop weighting) and 72.35% for solar radiation (5.31% lower than the deduced weighting and 32.95% higher than the workshop weighting). The weighting for the flood zone was set to be 8.33% (1.48% higher than the deduced weighting but 19.27% lower than the workshop weighting). This scenario indicated a higher preference on the economic factor and simulated a situation where decision makers prefer to develop larger sites and sites with a lower risk of flooding compared to the weightings deduced from the literature. This set of weightings was achieved by setting a score of 7 for solar radiation vs flood zone and a score of 5 for solar radiation vs site size. The site size vs flood zone comparison was scored 3, with a complete calculation shown in AHP Pairwise Summary – Scenario 1 for Solar PV in Appendix F.

Scenario 2 assigned both flood zone and site size the same weighting of 25% and solar radiation 50%. The purpose was to test the site priorities when decision makers place equal importance on site size and flood zone in identifying suitable sites and a higher emphasis on those criteria compared to Scenario 1. These were also effectively higher than the weightings deduced from literature, but slightly lower than the weightings yielded from the Inverse Linear scale. The weightings were systematically obtained by setting a score of 2 for both solar radiation vs flood zone and solar radiation vs site size comparisons, and a score of 1 for site size vs flood zone, illustrated in AHP Pairwise Summary – Scenario 2 for Solar PV and Wind Turbine in Appendix F. The consistency for the assigned weightings were checked as shown in section 8.2.3. The final solar PV scenario examined the results when assigning flood zone a higher importance than site size (19.32% for flood zone and 8.33% for site size). This was effectively a swap of weightings from Scenario 1 to observe the difference of site priorities if decision makers decide to prioritise the development for sites in lower risk of flooding over larger areas. Solar radiation weighting was sustained at 72.35% as in Scenario 1. In the AHP pairwise comparison, solar radiation vs site size was assigned a 7, solar radiation vs flood zone was assigned a 5 and flood zone vs site size was assigned a 3. A complete AHP process can be found in AHP Pairwise Summary – Scenario 3 for Solar PV and Wind Turbine in Appendix F.

For the WT site identification, the initial stage yielded a set of weightings of 72.35% for wind speed, 19.32% for site size and 8.33% for slope, consistent with decisions made in the literature. To test for changes in site priorities, three scenarios were also built to examine the effect of weightings to WT sites using user-defined weightings. The first scenario used a higher 78% weighting for wind speed (5.65% higher than the deduced weighting from Ayodele et al. (2018), Latinopoulos &

Kechagia (2015), Neufville (2013) and Tegou et al. (2010), 34.4% higher than the workshop weighting), 15.49% for site size (3.83% lower than the deduced weighting, 14.91% lower than the workshop weighting) and 6.85% for slope (1.48% lower than the deduced weighting, 19.15% lower than the workshop weighting). The comparison made using the MCDM workshop weighting were based on the set of weightings using the Inverse Linear scale. Scenario 1 weightings were similar to the weightings used in the solar PV case based on deduced weightings and were obtained by setting the values of wind speed vs slope comparison to 9, wind speed vs site size to 7 and site size vs slope to 3. The steps taken are shown in AHP Pairwise Summary – Scenario 1 for Wind Turbine in Appendix F.

Scenario 2 assessed an equal weighting of 25% for site size and slope in selecting WT sites, with a 50% weighting for wind speed to observe the difference of site priorities for WT installation, although the same set of weightings was also used for solar PV. The method to obtain these weightings are outlined in AHP Pairwise Summary – Scenario 2 for Solar PV and Wind Turbine in Appendix F. The final scenario used a higher slope importance than the land area, with a 19.32% weighting for slope and 8.33% site size. The weighting for wind speed was set to be the same as the value deduced from literature, at 72.35%. The set of weightings were obtained similar to the method applied in Scenario 3 for solar PV, shown in AHP Pairwise Summary – Scenario 3 for Solar PV and Wind Turbine in Appendix F. The weightings yielded from the sensitivity analysis process were all checked for consistency to be less than 0.1 (or 10%). For the sets of weightings that did not meet this criterion, they were not used and the judgement in pairwise comparison was rerun.

The weightings in all the scenarios have a large difference compared to the MCDM workshop weightings than weightings deduced from the literature due to the pairwise comparisons made using AHP-OS to obtain those weightings. Although many comparison values can be used to yield different weightings, these weightings were specifically used as they were checked to be consistent using the AHP consistency check that demonstrates a valid judgement in the pairwise comparison. A summary of all scenarios and weightings used in the analyses are shown in Table 8.12 and Table 8.13.

Table 8.12: Summary of scenarios.

	Solar PV	**Wind Turbine**
Weightings deduced from select literature	Highest weighting for solar radiation, followed by site size and flood zone.	Highest weighting for wind speed, followed by site size and slope.
MCDM workshop, Inverse Linear scale	Solar radiation lower than weightings consistent with solar site identification literature, site size and flood zone higher.	Wind speed lower than weightings consistent with WT site identification literature, site size and flood zone higher.
Scenario 1	Site size and flood zone have higher weightings but solar radiation has lower importance than weightings deduced from the literature but higher than using Inverse Linear.	Site size and slope have lower importance than weightings deduced from the literature and Inverse Linear, but wind speed has higher importance than earlier cases.
Scenario 2	Higher weighting for solar radiation, equal weighting for site size and flood zone.	Higher weighting for wind speed, equal weighting for site size and slope.
Scenario 3	Flood zone has higher importance than site size, but lower than solar radiation.	Slope has higher importance than site size, but lower than wind speed.

Table 8.13: Sensitivity analysis weightings.

	Solar PV			**Wind Turbine**		
	Solar Radiation	Site Size	Flood Zone	Wind Speed	Site Size	Slope
Scenario 1	72.35%	19.32%	8.33%	78.00%	15.49%	6.85%
Scenario 2	50.00%	25.00%	25.00%	50.00%	25.00%	25.00%
Scenario 3	72.35%	8.33%	19.32%	72.35%	8.33%	19.32%

8.6 Stages of Spatial Analysis for Solar PV

Three stages of spatial analysis were undertaken for each technology using relevant criteria by incorporating them into ArcGIS ModelBuilder. ModelBuilder is an application used to create, edit and manage models, which strings workflows of tools together, to produce a sequence of geoprocessing tools (detailed explanation in section 8.8). The three stages are detailed as follows:

8.6.1 Stage 1: Elimination of unfeasible sites based on restriction criteria

Certain criteria pose physical limitations that make installations unfeasible. The restrictions are based on the Boolean relation (true/false) and limit the study area to specific sites. For solar PV, north-oriented sites were categorised in this restriction. This is due to the sites facing due north receive the lowest solar radiation (SolarPV, 2017). Using the Shuttle Radar Topography Model (SRTM) obtained from EarthExplorer (USGS, 2017), aspect map was generated in ArcGIS and further reclassified according to site orientations.

8.6.2 Stage 2: Rating of attributes within the evaluation criteria and the application of AHP Weightings

After eliminating unfeasible aspects, the ratings of the evaluation criteria described in sections 7.4.1 through 7.4.6 were applied in the overlay process. Simultaneously, this overlay process took in the criteria weightings produced using the AHP method. The criteria selected for the solar PV installation in this research are tabulated in Table 8.14 with their respective ratings and classifications used in ModelBuilder.

Table 8.14: Classification used in ModelBuilder for ratings of various criteria.

Classification used in ModelBuilder	Solar radiation (kWh/m2/day)	Site size (ha)	Assigned rating	Flood risk	Risk band
10	2.727 – 2.9	50.0 – 109.0	1.0	Very low	4
9	2.554 – 2.727	10.0 – 50.0	0.9		
8	2.381 – 2.554	5.0 – 10.0	0.8		
7	2.208 – 2.381	1.0 – 5.0	0.7	Low	3
6	2.035 – 2.208	0.5 – 1.0	0.6		
5	1.862 – 2.035	0.4 – 0.5	0.5		
4	1.689 – 1.862	0.3 – 0.4	0.4	Medium	2
3	1.516 – 1.689	0.2 – 0.3	0.3		
2	1.343 – 1.516	0.1 – 0.2	0.2		
1	1.17 – 1.343	0.0 – 0.1	0.1	High	1
0	< 1.17	NoData	0.0	N/A	N/A

At this stage, different AHP weightings were applied to the relevant criteria in Table 8.14. Weightings deduced from the literature, the MCDM workshop and scenarios built were appended to the criteria in ModelBuilder to compare their results. The spatial analysis was done iteratively to measure and validate the differences of final scores in the brownfield site priorities.

8.6.3 Stage 3: Combining sites that pass the restriction criteria with the rated attributes

Using the preliminary feasible sites identified in Stage 1, the criteria ratings and weightings in Stage 2, the final overlay process combined all three components. The result was then overlaid with brownfield sites to identify their priorities based on the final evaluation layer. Once the sites were identified suitable for solar PV, similar methods were applied to identify feasible sites for WT, as elaborated in section 8.7.

8.7 Stages in Site Identification for Wind Turbine

In this research, the site selection was conducted to accommodate both utility-scale horizontal WT and vertical urban WT. The limiting criteria selected were imposed to prevent environmental and social conflicts for utility-scale WT. This is also the most suitable type of WT for large empty brownfield sites. Alternatively, for sites with existing infrastructure, vertical urban WT can be installed. As literature is lacking in urban WT siting for brownfield, this research identified suitable brownfield sites with potential to host both types of WT. The same selection criteria applied for small urban WT as for utility-scale WT. Three main types of WT are introduced in Table 8.15. The parameter values are representative examples.

Table 8.15: Types of WT considered (Norvento, 2018; Enercon, 2016b; Aeolos, n.d.).

Type	Example model	Rated power	Rated wind speed	Hub height	Rotor diameter
Utility	Enercon E82	3 MW	16 m/s	84 m	82 m
Medium	Norvento nED-100	100 kW	10 m/s	24.5 m	22 m
Small	Aeolos-V 10kW	10 kW	11 m/s	5.3 m	4.2 m

Considering the above types of WT, criteria explained in section 7.5 were applied to eliminate unsuitable sites beyond the wind energy constraints before being evaluated based on the criteria ratings. The elimination steps and evaluation processes were built into ModelBuilder in the same manner as for solar PV.

8.7.1 Stage 1: Elimination of unfeasible sites based on restriction criteria

For wind energy, the preliminary constraints were distance from protected areas (500 m) and distance from airports (2.5 km) (explained in sections 7.5.5 and 7.5.6). The values were inserted into ModelBuilder's tool to create a buffer area for both layers. The layers were converted into binary denotation, with 1 indicating feasible areas and 0 unfeasible. Both layers were combined using Raster Calculator with equal weighting to produce the restriction layer.

8.7.2 Stage 2: Rating of attributes within the Evaluation Criteria and the Application of AHP

Like the steps taken for the solar PV site identification, the evaluation criteria for wind farms were assessed based on their importance. The relevant criteria discussed in section 7.5.1 to section 7.5.6 were rated and classed as tabulated in Table 8.16. Thereafter, weightings deduced from the solar and WT site identification studies and the MCDM workshop were applied in the evaluation model. The iterative spatial analysis was performed to observe the differences in final scores in the brownfield priorities.

Table 8.16: Classification used in ModelBuilder for ratings of WT installation criteria.

Classification used in ModelBuilder	Wind speed (m/s)	Site size (ha)	Slope (°)	Assigned rating
10	8.94 – 9.57	50.0 – 109.0	0 – 7	1.0
9	8.31– 8.94	10.0 – 50.0		0.9
8	7.68 – 8.31	5.0 – 10.0		0.8
7	7.05 – 7.68	1.0 – 5.0	7 – 16	0.7
6	6.42 – 7.05	0.5 – 1.0		0.6
5	5.79 – 6.42	0.4 – 0.5		0.5
4	5.16 – 5.79	0.3 – 0.4	16 – 30	0.4
3	4.53 – 5.16	0.2 – 0.3		0.3
2	3.90 – 4.53	0.1 – 0.2		0.2
1	3.27 – 3.90	0.0 – 0.1	30 – 41	0.1
0	N/A	NoData	>41	0.0

8.7.3 Stage 3: Combining sites that pass the restriction criteria with the rated attributes

The sites in feasible areas (score 1) in Stage 1 were further filtered with the evaluation layer from Stage 2. After the combination using the Spatial Join function in ModelBuilder in both Stages, the final results were obtained. The results using various weightings are presented in Chapter 9.

8.8 ModelBuilder Process for Solar PV and WT

Each layer was created using the relevant criteria for corresponding RE technology. To create the restriction layer for solar PV, the data from the Shuttle Radar Topography Model (SRTM) was converted using the Aspect function in ArcGIS to obtain orientations for the entire GM. The layer was then reclassed to determine suitable aspects before the final raster layer was converted to polygon and overlaid with brownfield data.

Similar reclassification technique was used to create the evaluation layer using solar radiation, site size and risk of flooding. The reclassed layers were then overlaid using AHP weightings obtained from AHP to produce the evaluation layer. It was finally overlaid with the brownfield sites passing the first stage. Both ModelBuilder steps are shown in Appendix H.

For WT, four protected areas were combined to create a 500-m buffer zone. The protected area buffer was then combined with a 2,500-m buffer airport area. Using Raster Calculator, both buffer zones were reclassed as binary (1/0) to produce the final restriction layer. It was then overlaid with the brownfield data. The resulting sites were outside the exclusion area. To produce the evaluation layer, the same SRTM data was used to produce the slope layer. Site size and wind speed data were also reclassified before combined with the slope layer to yield the final evaluation layer. For all the reclassed criteria, a scale value of 0 to 10 was used, embedding the AHP weightings into the computation. The final layer was then overlaid with the brownfield sites that pass the restriction rule. Steps of how these processes were executed in ModelBuilder are demonstrated in Appendix H.

8.9 Identifying GSHP-Suitable Brownfield

This research examined the possibility to install GSHP systems at all available brownfield sites to help increase the implementation of district heating. Maps of bedrock and superficial deposits were analysed and the outcome revealed that the GM region has a combined bedrock consisting of mudstone, siltstone, sandstone, coal, ironstone and ferricrete, depicted in Figure 8.1. The areas with mudstone and siltstone which have a higher conductivity level are located mainly across the north of GM and the Pennines in the east. Mudstones can be found within a few metres of a ground surface.

Busby et al. (2009) suggested that chalky areas are also suitable for closed-loop collector systems, where the same fluid flows down the pipe and back up to the system heated. However, there was no chalk area recorded in GM. Due to the lack of information available in the literature on how non-residential sites can be utilised and prioritised for GSHP installations, brownfield sites in GM were prioritised using the criteria discussed in section 7.6. Using the data available in Figure 8.1, regions were prioritised according to the thermal conductivity level for different bedrocks and residential population. This was because bedrock characteristics were important for borehole type of GSHP whereas superficial deposit characteristics were important for shallow trench GSHP (British Geological Survey, 2011; Busby, et al., 2009).

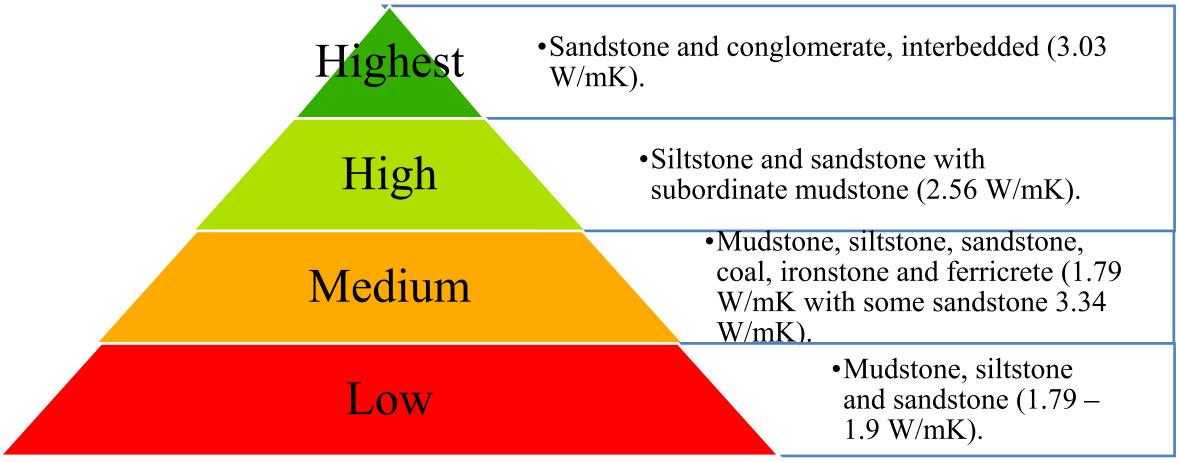


Figure 8.1: Classification of bedrock used for site prioritisation.

Due to the unavailability of thermal conductivity data for superficial deposits, their ranking was omitted in this research, forcing the limitation of borehole GSHP implementation. In projects where trench type of GSHP is involved, however, it is crucial to analyse the thermal conductivity for superficial deposits due to the shallowness of the system (between 1-2 m) and might be covered by superficial deposits. Similar steps of prioritisation can be adopted to evaluate a large region for trench type of GSHP.

Although most of the areas in GM have a superficial thickness of up to 30 m, the thickness can be up to 80 m before reaching the bedrock in some regions (shown in Map 7.10). When developing GSHP systems in areas with thick superficial deposits, it is important to examine their thermal characteristics which play a big role in determining the heat transfer and the efficiency of the system. Considering the available thermal conductivity data for bedrock, the data was combined with the population density data to identify site priorities for GSHP installation.

8.10 ModelBuilder Process for GSHP

As there were only two criteria considered for the placement of GSHP, the AHP method was not applied as it was not necessary. The bedrock layer was classified into 4 classes, indicated by their thermal conductivity. Urban areas were classified into 10 classes as explained in section 7.6.2. Both layers were then combined with equal importance using the Weighted Overlay function. Spatial Join was then performed to identify feasible sites for GSHP installation once the evaluation layer was produced. A complete ModelBuilder process can be found in Appendix H.

8.11 Summary

This chapter explained the steps to elicit manual weightings using AHP. Next, the criteria weightings obtained from a pilot workshop were analysed. They were differentiated using different scales. A similar analysis was performed using the MCDM workshop results to validate the methods and findings. From the weightings deduced from solar and WT site identification studies and MCDM workshop, three scenarios were built with different sets of weightings as a sensitivity analysis.

All the deduced weightings, weightings from the MCDM workshop and sensitivity analysis are summarised in Table 8.17. From the table, the weightings deduced from previous studies favoured a much higher importance for the fuel factor for each technology. This directly reduced the importance of flood zone and slope a lot. The largest difference between the two criteria was 70.81%.

For the weightings from the MCDM workshop, a smaller difference was observed among all weightings due to the low-dispersion scales selected. Considering that the Inverse Linear scale works best with the highest consensus, the highest difference between criteria is only 17.6%, observed in the WT set when comparing slope and wind speed.

Table 8.17: Summary of weightings from various sources.

		Solar PV			Wind Turbine		
		Solar Radiation	Site Size	Flood Zone	Wind Speed	Site Size	Slope
Deduced from Previous Studies		77.66%	15.49%	6.85%	72.35%	19.32%	8.33%
MCDM Workshop	**Inverse Linear**	39.40%	32.90%	27.60%	43.60%	30.40%	26.00%
	Balanced	43.00%	32.40%	24.60%	48.90%	28.40%	22.70%
Sensitivity Analysis	**Scenario 1**	72.35%	19.32%	8.33%	78.00%	15.49%	6.85%

Table 8.17 (continued).

Sensitivity Analysis	**Scenario 2**	50.00%	25.00%	25.00%	50.00%	25.00%	25.00%
	Scenario 3	72.35%	8.33%	19.32%	72.35%	8.33%	19.32%
Legend:	75 – 100%	50 – 75%	30 – 50%	10 – 30%	0 – 10%		

The chapter then focussed on the stages for the site identification process, combining the use of AHP and GIS. The process was executed in three stages, with the AHP results applied in the second stage. The AHP method was used to compare the evaluation criteria to produce weightings. It was chosen over other MCDM methods due to its relevance/suitability for this type of non-monetary evaluation.

Although the method was applied to establish weightings for solar PV and WT, it was not applied to identify sites for GSHP since there were only two criteria considered. Equal weighting was considered for both criteria. Nevertheless, ModelBuilder was used for all three processes as it aided the iterative analysis.

Chapter 9 presents the results of the site identification process using all the weightings outlined in this chapter and discusses the findings. The results using weightings from the MCDM workshop are compared to the ones used in previous studies to observe any differences. Chapter 10 then discusses the overall process conducted in this research to build a transferable process model.

Chapter 9 : GIS Analysis Results and Discussion

9.1 Introduction

This chapter presents the spatial analysis results using various sets of weightings for the evaluation criteria in the spatial analysis. The results presented in this chapter begin with brownfield site prioritisation using weightings deduced from the literature, followed by a brief overview of the pilot workshop and the weightings from the multicriteria decision making (MCDM) workshop. Results of the sensitivity analysis are then presented. Assessments are conducted after each presentation.

Prioritised brownfield sites for solar PV and wind turbine (WT) installations are presented in sections 9.2, 9.3, 9.4, followed by brownfield site prioritisation for ground source heat pump (GSHP) placement in section 9.5. Following the GSHP site evaluation, a discussion on the GIS analysis, MCDM method and Analytic Hierarchy Process (AHP) workshop, criteria weightings and policy implications are presented before this chapter is summarised. Maps for all the different scenarios and results are included at the end of this chapter.

9.2 Site Evaluation Scores Using Weightings Deduced from the Literature

For solar PV, the weightings derived from Al-Garni & Awasthi (2017), Georgiou & Skarlatos (2016) and Carrión et al. (2008) that are consistent in their sequence produced the spatial analysis results in Table 9.1. The weightings used were 77.66% for solar radiation, 15.49% for site size and 6.85% for flood zone. Results with a higher Evaluation score indicate a higher preference and vice versa. The scores are colour coded throughout this chapter to ease interpretation. The scores in Table 9.1 are plotted in Map 9.1.

Table 9.1: Brownfield scores for solar PV installation using literature-consistent weightings.

Evaluation score	Number of brownfield sites
10	0
9	2
8	324
7	696
6	190
5	0
4	0
3	0
2	0
1	0

The brownfield site identification for WT used 72.35% for wind speed, 19.32% for site size and 8.33% for slope, as discussed in sections 8.2.4 to 8.2.6. The spatial analysis yielded the results in Table 9.2; these are shown in Map 9.2.

Table 9.2: Brownfield scores for WT installation using literature-consistent weightings.

Evaluation score	Number of brownfield sites
10	0
9	0
8	0
7	0
6	1
5	16
4	102
3	201
2	2
1	0

9.2.1 Assessment on the Results Using Weightings Deduced from the Literature

In Table 9.1, only two brownfield sites scored 9 for the solar PV case from the analysis using weightings deduced from Al-Garni & Awasthi (2017), Georgiou & Skarlatos (2016) and Carrión et al. (2008). The range of the scores was rather small, which arose from the large difference of criteria weightings between the highest and lowest (also known as weighting distribution). Overall, three hundred and twenty-four (324) sites received a score of 8, followed by 696 sites with a score of 7 and 190 sites with a score of 6. In this case, sites receiving a score of 9 are prioritised, followed by sites with a score of 8.

Observing Table 9.2, the range of scores is low, with a maximum score of 6 and a minimum of 2. The scores achieved by brownfield sites were also low, with only one site scoring 6 while most sites scored 3. The range of scores was reduced for WT installation compared to solar PV. This reduction could be a result of the different values within the criteria used and their classification. Due to the unavailability of sites with a score greater than 6, sites with a score of 6 should be investigated for development.

9.3 Site Evaluation Scores Using Weightings from MCDM Workshop

From the pilot workshop, the Inverse Linear scale performed the best among all of the scales available within AHP-OS (highlighted in sections 8.3 and 8.4). The results for spatial analysis using the MCDM workshop weightings are presented for this scale, comparing with the second-best scale, the Balanced scale. A summary of criteria weightings from both scales is shown in Table 9.3.

Table 9.3: Summary of criteria weightings from the MCDM workshop.

Scale	**Solar PV**			**Wind Turbine**		
	Solar Radiation	Site Size	Flood Zone	Wind Speed	Site Size	Slope
Inverse Linear	39.4%	32.9%	27.6%	43.6%	30.4%	26.0%
Balanced	43.0%	32.4%	24.6%	48.9%	28.4%	22.7%

The number of brownfield sites is ranked according to their final scores in Table 9.4 and Table 9.5 for solar PV installation and WT installation respectively. Results for both solar PV and WT installations are mapped in Map 9.3 to Map 9.6.

Table 9.4: Number of prioritised brownfield sites for solar PV using weightings from the MCDM workshop.

Evaluation Score	Inverse Linear	Balanced
10	0	0
9	22	21
8	283	258
7	274	273
6	503	545
5	86	75
4	28	39
3	16	1
2	0	0
1	0	0

Table 9.5: Number of prioritised brownfield sites for WT using weightings from the MCDM workshop.

Evaluation Score	Inverse Linear	Balanced
10	0	0
9	0	0
8	0	0
7	2	0
6	73	46
5	84	77
4	162	198
3	1	1
2	0	0
1	0	0

9.3.1 Assessment on the Results Using Weightings from the MCDM Workshop

The results in Table 9.4 show a higher number of brownfield sites in the highest score using the Inverse Linear scale. The distribution of results is overall better using this scale due to the high number of sites located in the top three scores. Although the highest number of sites are in the score 6 region (503 sites), similar to the result using the Balanced scale, the availability of more sites in the higher scores means more developments are feasible yielding higher energy output. This pattern arises because the spatial analysis prioritises areas with higher solar radiation, higher hectarage and a lower risk of flooding.

The weighting distribution using different scales in Table 9.3 shows a smaller dispersion produced by the Inverse Linear scale. The most important criterion, solar radiation has a lower weighting (39.4%) compared to using the Balanced scale (43%). This contributed to the highest number of brownfield sites in the highest- and second-highest scores (9 and 8). However, this scale also yielded a high number of sites in the lowest-score (3). Overall, the results using Inverse Linear and Balanced scales were comparable. Although the Inverse Linear scale yielded the highest group consensus, the dispersion of weights played a more significant role in determining the final score. Similar to the earlier cases using deduced weightings, sites in score 9 are prioritised.

For WT installation, Table 9.5 shows the best results using the Inverse Linear scale with more sites in the highest-available score. Based on Table 9.5, a noticeable difference is seen for WT installation. Two sites received a score of 7 using the Inverse Linear scale, but none using the Balanced scale. Also, with the Inverse Linear scale, more sites received a final score of 6 and 5 compared to the Balanced scale. Notably, 36 more sites had a score of 4 if the Balanced scale was used, rather than the Inverse Linear scale. This demonstrates the effect of smaller weighting dispersion. Sites with a score of 7 for WT installation should be investigated for development as there was no site with a higher score.

From the comparison of site prioritisations, the Inverse Linear scale is the best to be used for both solar PV and WT site identification. The scale does not only yield the highest group consensus but also a more balanced distribution in weightings which results in a wider feasible region. Analysis using this scale produced a higher number of prioritised brownfield sites for development.

9.4 Sensitivity Analysis Scores

Besides the deduced weightings from previous studies and the weightings obtained from a workshop, three scenarios were built to study how the different weightings affect the evaluation scores of brownfield sites as elaborated in section 8.5, Table 8.12 and Table 8.13. The scenarios and their weightings are presented in Table 9.6 with the results for solar PV site identification in Table 9.7 and WT in Table 9.8. Maps for all scenarios are shown in Map 9.7 to Map 9.12 in section 9.8.

Table 9.6: Criteria weightings for three scenarios.

	Solar PV			Wind Turbine		
	Solar Radiation	Site Size	Flood Zone	Wind Speed	Site Size	Slope
Scenario 1	72.35%	19.32%	8.33%	78.00%	15.49%	6.85%
Scenario 2	50.00%	25.00%	25.00%	50.00%	25.00%	25.00%
Scenario 3	72.35%	8.33%	19.32%	72.35%	8.33%	19.32%

Table 9.7: Number of prioritised brownfield sites for solar PV sensitivity analysis.

Evaluation Score	Scenario 1	Scenario 2	Scenario 3
10	0	0	0
9	5	22	9
8	275	335	796
7	672	599	340
6	251	186	60
5	9	53	7
4	0	17	0
3	0	0	0
2	0	0	0
1	0	0	0

Table 9.8: Number of prioritised brownfield sites for WT sensitivity analysis.

Evaluation Score	Scenario 1	Scenario 2	Scenario 3
10	0	0	0
9	0	0	0
8	0	0	0
7	0	0	0
6	1	76	3
5	19	95	96
4	115	151	221
3	185	0	2
2	2	0	0
1	0	0	0

9.4.1 Assessment on the Sensitivity Analysis Results

The results in Table 9.7 and Table 9.8 show a consistent pattern where Scenario 2 (using 50% for solar radiation/wind speed, 25% for site size and 25% for flood zone/slope) in both technology applications yield the highest number of brownfield sites in the maximum score. The second-highest score (8 for solar PV, 5 for WT) has a considerably large number of brownfield sites, although the third-highest score is where most sites are located.

In Table 9.7, Scenario 3 yields fewer sites in score 9 than Scenario 2, although most of the sites are in score 8 (the second-highest). In Table 9.8, fewer sites receive a score of 6 but the majority are in the score of 4. It is apparent that although the weightings are the same for both applications (using 72.35% for solar radiation/wind speed, 8.33% for site size and 19.32% for flood zone/slope), the result patterns are different. This could be attributed to the classification of criteria in ModelBuilder (from 1 to 10) and values within each criterion.

Comparing the weightings consistent with the literature and Scenario 1, the difference in criteria weighting is relatively small, resulting in a small difference of sites with higher scores for both technologies. However, when comparing Scenario 1 and Scenario 3 for solar PV where the weightings for site size and flood zone are swapped, the significant difference is in the second-highest score, where a higher number is obtained when flood zone is more preferred over site size. The same pattern is also observed for WT when comparing the same set of literature consistent weightings and Scenario 3, where higher slope importance shows the largest number of feasible sites in the second priority.

When a comparison is made between the MCDM and the sensitivity analysis results, for solar PV installation, Scenario 2 gives a slightly better result with 52 more brownfield sites in score 8 than using the Inverse Linear scale. The result in Scenario 2 also has 325 more sites in score 7 comparing with the Inverse Linear result. The higher scoring sites in Scenario 2 cause the range of scores to be higher, with no site receiving the lowest score, as observed using the Inverse Linear scale. It needs to be noted, however, that Scenario 2 is tested using special 50%-25%-25% weightings which are difficult to achieve if the weightings are determined by a group of decision makers. This does not mean that it is impossible to achieve, as demonstrated in Appendix F.

Regarding the WT installation, the Inverse Linear scale provides a better result with 2 sites in the highest score, 7. This is not seen in the results applying other weightings although Scenario 2 produces the highest number of sites in the score 6 region among all scenarios. Furthermore, Scenario 2 yields no site in scores 3 and 2, unlike all other results. The 50% weighting for wind speed in

Scenario 2 yields a better result than weightings greater than 70%, as applied in Scenarios 1 and 3. Using the Inverse Linear scale from the MCDM workshop, when wind speed is assigned 43.6% weighting with the lowest weighting dispersion, the score of 7 is produced. This demonstrates the need for balanced weightings when considering site size and slope alongside wind speed.

All the differences in the site priorities could be attributed to a few reasons: 1) the weightings assigned to each criterion in the consideration; 2) the interval rating for each criterion; 3) the criteria selected for the technology. The similarity of pattern in the number of site priorities can be seen in both applications where the lower the weighting for the fuel factor (solar radiation/wind speed), the higher the number of sites in the high score. This could be directly linked to the higher interval values in other criteria (site size, slope, flood zone) that influence the final evaluation computation. When these criteria were given low importance, the overall score decreased even though the perceived most important factor (fuel factor) was assigned high importance.

The way the values within each criterion was classified in intervals and rated also influenced the final site evaluation score. This was especially true for site size, wind speed and solar radiation, where a decimal difference in values could place the interval in a higher or lower rating. For example, if a solar radiation value of 2.73 kWh/m^2/day was grouped together with the 2.554 kWh/m^2/day, any site having that amount of radiation would be rated as 0.9 in the ModelBuilder classification, giving a lower rating in the computation. This would subsequently reduce the final evaluation score. The case was slightly different for flood zone which had a fixed classification of less than 10. In this case, all sites were already situated in a specific 'risk band' of flooding and the values would not change in the final evaluation.

The analysis using a different set of weightings shows that a certain set of weightings can place more sites in the ideal region (best score), while another set can reduce the scores. Although the exact values of the criteria preference were different from what were used in the literature, the deduction was made to determine what is perceived as more/less important due to criteria used in previous studies. The sensitivity analysis was conducted with the same sequence of criteria importance parallel with the literature, except for Scenarios 2 and 3 so the effect of weightings could be examined.

9.5 Site Evaluation Scores for GSHP Placement

GIS analysis was performed utilising the available thermal conductivity data for bedrock combined with the residential population data. This yielded suitable areas for borehole GSHP installation. The investigation of brownfield locations with respect to bedrock thermal conductivity levels shows that most sites are in the medium priority zone, with a combination of mudstone, siltstone, sandstone coal, ironstone and ferricrete. A complete list of sites and bedrock priority is shown in Table 9.9 and Map 9.13.

Table 9.9: Feasible sites for GSHP corresponding to bedrock priorities.

Bedrock priority	Number of sites	Percentage
Highest	514	39.12%
High	3	0.22%
Medium	649	49.39%
Low	148	11.26%

After combining the bedrock data with the residential population and running the ModelBuilder process applying equal weightings, the results in Table 9.10 are obtained. The locations of the sites are plotted in Map 9.14.

Table 9.10: Site priorities for GSHP installation.

Grade of Evaluation layer	Number of sites	Priority
10	40	Highest
9	49	
8	231	High
7	146	
6	80	Medium
5	167	
4	349	Low
3	195	
2	44	
1	13	Lowest

From the results in Table 9.9 which are mapped in Map 9.13, there is almost 40% of the total number of sites located in the highest thermal conductivity for bedrock. Utilising this advantage and combining it with the residential population data, the spatial analysis yielded a result of a high concentration of sites in the ‘high’ and ‘low’ priority regions. Note that this analysis is valid for borehole GSHP installations only. If trench type of GSHP is considered with data availability, similar steps can be performed in ModelBuilder to prioritise superficial deposit instead of bedrock.

9.6 Vignettes of Potential Sites

Following the findings from the site identification process, this section provides a brief review of sites with the highest potential, indicated by the highest final score. For solar PV installations, two sites with a score of 9 using the Inverse Linear scale are exemplified, while for WT installation, two sites having a score of 7 are exemplified. One site is exemplified for GSHP installation considering the borehole system. The brief vignettes illustrate the sites in a broader context, the location of the site, the description of the site suitability based on the criteria used for assessment (wind speed, solar radiation, slope, bearing, thermal conductivity, site size) and the reflection on necessary matters (for instance, suitability for GSHP (borehole versus trench), flood risk consideration and neighbouring residential areas).

9.6.1 Solar PV Site 1: South of Hindley, Wigan

- Site reference: SHLAA0002
- Coordinates: 53.5239, -2.5677
- Site size: 109 ha (1,090,000 m^2)
- Solar radiation: 2.357 $kWh/m^2/day$
- Flood risk band: 4 – very low
- Owner: Mixed ownership

This site scored 9 in the final evaluation score based on the criteria classes used in ModelBuilder which are 7 for solar radiation, 10 for flood risk and 10 for site size. This is the largest site among all the available brownfield sites. It faces east-northeast with a bearing of 63° and has a slope of 0.6°. Figure 9.1 and Figure 9.2 show the brownfield site in the South of Hindley in a broader context in Wigan, which is near resident areas, and Map 9.1 shows a satellite view. Should this site be chosen for development, neighbouring residents should first be consulted on their agreement for solar farm development to proceed, to enhance locally produced renewable energy that can benefit local residents.

Figure 9.1: Google Street view showing site at South of Hindley, Wigan located nearby a residential area.

Figure 9.2: View of South of Hindley, Wigan brownfield site from a nearby roundabout.

Map 9.1: Satellite view of South of Hindley brownfield.

9.6.2 Solar PV Site 2: Land at Former Horwich Loco Works, Bolton

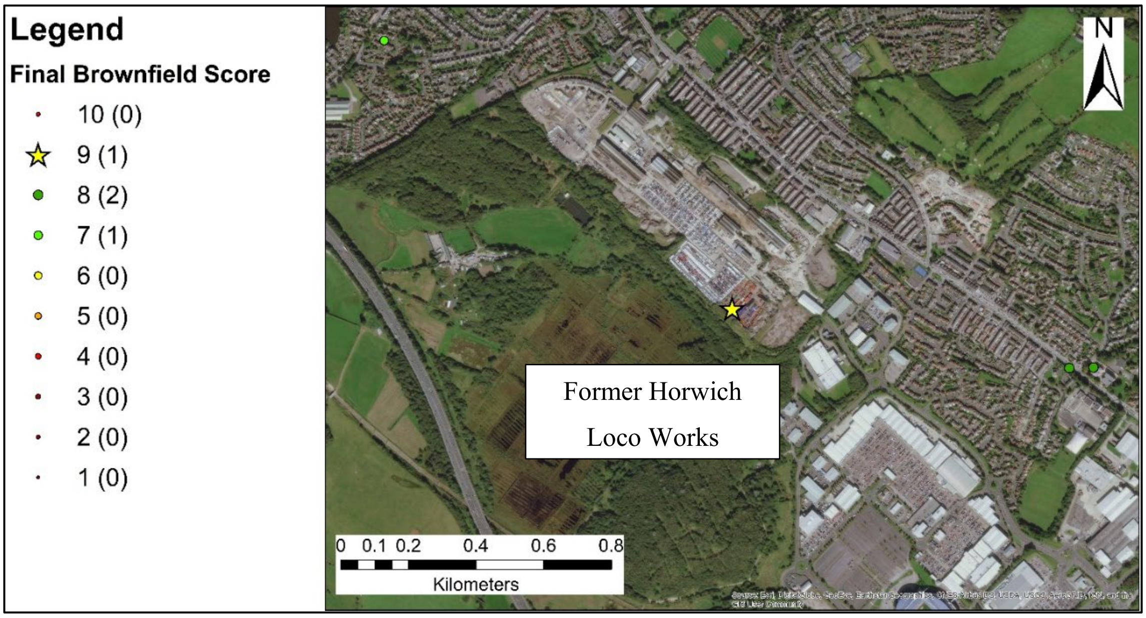
- Site reference: 19-BOL
- Coordinates: 53.58874, -2.543207
- Site size: 76.7 ha (767,000 m^2)
- Solar radiation: 2.397 kWh/m^2/day
- Flood risk band: 4 – very low
- Owner: Mixed ownership

The second site scored 9 in the final evaluation score based on the criteria classes used which are 8 for solar radiation, 10 for flood risk and 10 for site size. The site has an area of 76.7 hectares, faces east-southeast with a bearing of 126° and has a slope of 1.3°. Although this large site is a former industrial site, it is surrounded by residential areas and located not far from road access, as seen in

Figure 9.3, Figure 9.4 and Map 9.2. For development consideration, similar to the site in 9.6.1, neighbouring residents should be consulted for solar farm development to avoid opposition.

Figure 9.3: Google Street view showing land at former Horwich Loco Works, Bolton.

Figure 9.4: Another angle of the land at Horwich Loco Works, Bolton.



Map 9.2: Satellite view of land at former Horwich Loco Works, Bolton.

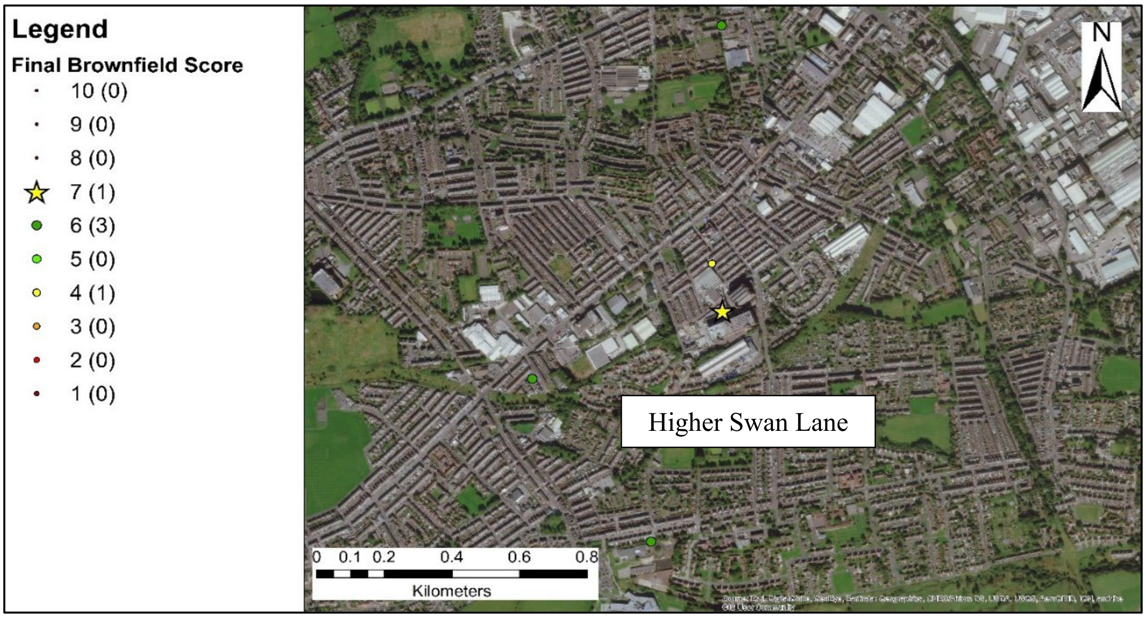
9.6.3 Wind Turbine Site 1: Higher Swan Lane, Bolton

- Site reference: 3P6AP-BOL
- Coordinates: 53.56343, -2.44331
- Site size: 11.55 ha (115,500 m^2)
- Wind speed: 5.1 m/s
- Slope: 4.3°
- Owner: Mixed ownership

This site scored 7 in the final evaluation score for WT installation using wind speed, slope and site size as selection criteria with classes of 3, 10 and 9 respectively. With the relatively flat land structure at the site and proximity to the main road, WT installation should not be risky. However, as the site is located close to residences, small HAWT or urban VAWT should be considered instead of large-scale utility WT to reduce safety hazards and noise pollution. Local residents should also be made aware of the site potential for WT development due to its strategic location for RE generation.

Figure 9.5: Google Street view facing southwest showing brownfield site at Higher Swan Lane which still has a structure.

Figure 9.6: Google Street view facing northwest. This 11.55 ha site hosts several buildings.



Map 9.3: Satellite view of Higher Swan Lane brownfield site.

9.6.4 Wind Turbine Site 2: Gorton Central Masterplan Area, Manchester

- Site reference: Gort_N_Cap_026
- Coordinates: 53.46212, -2.185836
- Site size: 15.49 ha (154,900 m^2)
- Wind speed: 4.8 m/s
- Slope: 1.9°
- Owner: Unknown ownership

This site scored 7 in the final evaluation score for WT installation using wind speed, slope and site size as selection criteria with classes of 3, 10 and 9 respectively. This site has flat land with a slope of around 2°, close to a main road and residences and train stations. For WT installation, this site will be able to host urban VAWT instead of large-scale utility HAWT and take advantage of the high wind speed of around 4.8 m/s. Due to the unknown ownership of this site (based on GMCA record), further consideration has to be made in obtaining development permission.

Figure 9.7:Google Street view facing west showing Gorton Central Masterplan Area brownfield site.

Figure 9.8: Google Street view facing east of Gorton Central brownfield site.

Map 9.4: Satellie view of Gorton Central Masterplan Area brownfield site.

9.7 Discussion

This section discusses the findings of the spatial analysis and how they link to the discussion in earlier chapters. Section 9.7.1 focuses on the outcomes of GIS analysis; section 9.7.2 explores the relationship of the MCDM method, AHP and workshop run in this research with past executions in the literature; section 9.7.3 examines the effectiveness of the criteria weightings used and section 9.7.4 discusses the relation between policies involving brownfield, RE and RH and this research.

9.7.1 Discussion on the Outcomes of GIS Analysis

The outcomes of the spatial analysis in this chapter demonstrate that the prioritisation of brownfield sites can be influenced by three factors, namely:

1. Criteria selected for the technology;
2. The intervals of the criteria values;
3. The weightings of each criterion.

For solar PV and WT installations, various weightings were used by different decision making groups in the literature and it is apparent that different weightings can produce different final evaluation score (Georgiou & Skarlatos, 2016; Latinopoulos & Kechagia, 2015).

Scores 10 and 9 are classed as the top priority for development for all technologies, as used in Georgiou & Skarlatos (2016) and Tegou et al. (2010). In most of the solar PV outcomes (Table 9.11 in section 9.6.3), the maximum number of brownfield sites is in the median value which indicates a bell curve distribution. For WT however, the maximum number is found in the lower scores (Table

9.12). This is caused by the interval value of the criteria used, which subsequently yields a lower number of sites in the highest score. A similar pattern was observed in studies by Villacreses et al. (2017), Sánchez-Lozano et al. (2015), Watson & Hudson (2015), and Tegou et al. (2010).

For the GSHP placement analysis, an equal weighting was assigned to both criteria. Due to the location of almost half of the sites in the medium score of thermal conductivity level, the final combined score was skewed to the lower limit placing most sites in scores 4 and 3 (Table 9.10). Despite that, there are still more than 300 sites located in the highest and high priority regions.

The application of GIS in this research was also accompanied by the built-in feature, ModelBuilder, which aided repetitive tasks to be run (Esri, 2016c). In ModelBuilder, steps taken were recorded and consolidated as executable models and were saved and transferred in geodatabases. Three advantages were reaped by utilising ModelBuilder in this research (Ibid.):

1. The ability to tweak the criteria to match the technology and save an existing model as a new model;
2. The ability to tweak the weightings of the evaluation criteria for different scenarios;
3. The ability to work on multiple machines using the same model.

The use of ArcGIS for the selection of feasible sites addressed the fourth research objective, which helped to achieve the prioritised results more efficiently. This methodology can be applied in other spatial contexts by adapting the evaluation and restriction criteria to match the relevant legal framework or policies. As such, the method can be generalised to apply any necessary spatial data.

9.7.2 Discussion on the MCDM Method, AHP and Workshop

This research adopted the MCDM method, specifically AHP, to evaluate the technical criteria in site selection. The AHP has been applied in research in various fields, as explained in Chapter 6. In energy planning, the use of AHP is favoured primarily due to its ease of understanding and execution and its ability to compute the consistency of a decision maker's judgement (discussed in section 6.4.6). In this research, AHP was beneficial in many ways that it helped the process of assigning criteria weightings for spatial analysis without the hassle of long computations and explanation to decision makers (as employed in section 8.4).

AHP was applied in a series of workshop throughout the course of this research to gauge participants' opinions on the importance of the selected criteria, as conducted in Georgiou & Skarlatos (2016), Sánchez-Lozano et al. (2016; 2015) and Watson & Hudson (2015). Due to the straightforward approach of pairwise comparison in AHP, all participants were able to easily understand the research, the method applied and how to use it. This is a crucial consideration especially when the decision needs to be made by people who are not familiar with the method. The workshop run demonstrated the ability of the method to simulate real-life planning projects and the ability of AHP to aggregate group decisions (Goepel, 2018).

The AHP method applied in this research utilised the free online software, AHP-OS which had a user-friendly interface and great user support. The software was developed with clear documentation of its approaches, making it easier for academics and non-academics to understand and justify the steps taken. Furthermore, the availability of the documentation online is an advantage to understanding the software, unlike some other commercial ones. This was a major advantage of this software compared to other commercial software that lacked complete explanations on their approaches and computations. Furthermore, decisions could be made online using different devices, giving multiple decision makers the convenience to collaborate without any software installation. Another advantage of AHP-OS was the availability of different scales to produce the final criteria weightings. The scales were useful for users to measure the dispersion of weightings and the effect of different absolute weightings on the final criteria score (Goepel, 2019). This was because the final scores determined the brownfield development priorities.

Although some users argue that the transitivity rule is important when applying the AHP, the straightforward approach of AHP-OS and the availability of consistency check before each decision is saved ensure that each pairwise comparison is consistent. Any inconsistent judgement made will be flagged with a warning. The AHP has a set limit of criteria that it can accept (usually ten), so the transitivity rule does not contribute to much difference when comparing a small number of criteria. The direct pairwise comparison of criteria up to ten can easily be made with the aid of the consistency check (Goepel, 2017).

9.7.3 Discussion on the Criteria Weightings

Three sources of weightings were employed for the spatial analysis of this research. The first set of weightings were deduced from previous studies to allow for the best results due to their preferred pairwise comparisons. However, not all the criteria applied in this research were available in the literature as they were not brownfield or GM specific. Therefore, a workshop was conducted involving experts with knowledge on brownfield, RE and the location to elicit criteria weightings. Such expert involvement was also employed in Lozano et al. (2016; 2015), Noorollahi et al. (2016a) and Neufville (2013) to ensure the validity of weightings.

The difference in weightings from various sources had a direct impact on the score of brownfield sites although it may not be significant for some. The weightings derived from previous studies that assigned solar radiation the highest importance yielded only 2 sites in the highest evaluation score (shown in Table 9.11). The same case was observed for WT installation when wind speed was assigned the highest weighting (one site in score 6).

To study how the results could be enhanced, an MCDM workshop was conducted to elicit criteria weightings. The aggregated pairwise comparisons contributed by the workshop participants yielded various sets of weightings which can be compared to the deduced weightings. This was parallel to the sequence applied in Al-Garni & Awasthi (2017), Villacreses et al. (2017), Georgiou & Skarlatos (2016) and Carrión et al. (2008) where the solar radiation was assigned the highest weighting, and parallel to Ayodele et al. (2018), Latinopoulos & Kechagia (2015), Neufville (2013) and Tegou et al. (2010) where wind speed was assigned the highest weighting followed by other geographical and environmental criteria. Although the sequence of criteria considered was similar, the results using the Inverse Linear and Balanced scales from AHP-OS produced completely different results. For solar PV, the prioritisation of brownfield sites resulting from the MCDM workshop was best using the Inverse Linear scale (Table 9.11) due to the smaller weight dispersion.

A sensitivity analysis was conducted to compare results using different weightings and to simulate different stakeholder or policy preferences in different circumstances (Díaz-Cuevas, 2018; Latinopoulos & Kechagia, 2015; DCLG, 2009). Based on the sensitivity analysis results, Scenario 2 produced the best result with the highest number of sites at the top of the score range for both solar PV and WT cases. Although the best result was achieved using these weightings, it needs to be noted that, however, this is only an ideal scenario where exactly 50% weighting is allocated to solar radiation/wind speed and equal weighting of 25% allocated to the other two criteria. In real life, when the weighting assignment is a collaborative effort, such a set of weightings might be difficult to achieve.

For the wind energy scenario, the highest score obtained using weightings consistent with the literature was only 6, whereas the Inverse Linear weightings produced 7 as the highest score (Table 9.12). It is apparent that the best result was achieved using the Inverse Linear scale and cannot be achieved using other sets of weightings, even the 50%-25%-25% weightings in Scenario 2.

Table 9.11: Number of brownfield sites prioritised for solar PV under different conditions.

Evaluation Score	Deduced from the Literature	MCDM Workshop		Sensitivity Analysis		
		Inverse Linear	Balanced	Scenario 1	Scenario 2	Scenario 3
10	0	0	0	0	0	0
9	2	22	21	5	22	9
8	324	283	258	275	335	796
7	696	274	273	672	599	340
6	190	503	545	251	186	60
5	0	86	75	9	53	7
4	0	28	39	0	17	0
3	0	16	1	0	0	0
2	0	0	0	0	0	0
1	0	0	0	0	0	0

Table 9.12: Number of brownfield sites prioritised for WT under different conditions.

Evaluation Score	Deduced from the Literature	MCDM Workshop		Sensitivity Analysis		
		Inverse Linear	Balanced	Scenario 1	Scenario 2	Scenario 3
10	0	0	0	0	0	0
9	0	0	0	0	0	0
8	0	0	0	0	0	0
7	0	2	0	0	0	0
6	1	73	46	1	76	3
5	16	84	77	19	95	96
4	102	162	198	115	151	221
3	201	1	1	185	0	2
2	2	0	0	2	0	0
1	0	0	0	0	0	0

The site identification for GSHP placement shows that equal weightings for both criteria gave an equal influence to the final results. In Map 9.14, the pattern of bedrock priorities is apparent in the final evaluation map, although it was combined with the values of the urban population in a finer grid. If the superficial deposit was used instead, the pattern would differ according to its thermal conductivity levels. If the thermal conductivity values are available and users prefer to identify sites for trench type of GSHP, they can easily replace the bedrock block in ModelBuilder with the superficial deposit data.

As a summary, the workshop involving experts in the field yielded useful results for the spatial analysis that aided in achieving the third and fourth objectives of this research: to engage with experts in deciding the importance of criteria in brownfield site selection and to undertake a spatial analysis using GIS to identify suitable brownfield sites to be developed.

9.7.4 Discussion on Brownfield, Renewable Energy and Renewable Heat Policies

The spatial analysis in Chapter 9 demonstrated that brownfield sites available in GM can be developed for RE and RH technologies. Using the criteria applied in this research, feasible brownfield sites can be identified using GIS. In Chapter 2, discussion on brownfields, their challenges for development and their related policies implemented in various countries show that brownfield sites are lucrative yet untapped resources for various purposes (Thomas, 2002; Rafson & Rafson, 1999; Dennison, 1998). Nevertheless, the policies implemented for brownfield development in the UK strongly focus on housing.

Although there are motivations to use brownfield land for temporary uses such as playgrounds, car parks and RE installations, in most scenarios, there is no specific guidance on the technicalities and parameters that need to be followed, only general guidance to identify suitable sites (for example, DCLG (2015b)). This resulted in research employing non-unified values for those parameters as elaborated in Chapter 7. Discussion on potential RE and RH technologies and their policies in Chapters 3 and 4 revealed that many policies exist in different countries to support the growth of renewables to help their zero-carbon objective (Sayegh, et al., 2017; Energy Technologies Institute, 2016; Wang, 2010; DCLG, 2006).

Earlier chapters established that the brownfield development for RE and RH is not a common practice in many countries, as more research is focused on identifying open parcels (for instance, desert, rural areas, offshore) for those technologies (Aly, et al., 2017; Jangid, et al., 2016; Kharseh, et al., 2015; Dolney & Flarend, 2013). This created a gap in guidance for the installation of such technologies at brownfield sites. To overcome this lack of information and assist authorities and governments to achieve their sustainability goals, this research has demonstrated that the purpose of brownfield development can be diversified with the implementation of solar PV, WT and GSHP that can support sustainable land development, RE and RH advancement.

In addition to powering the nation with sustainable energy available in the environment, the use of district heating can also boost the market of new development areas (Bioregional, 2015). The availability of brownfield sites in GM shows that they can be great resources to extract heat from the ground and supply new district heating systems. Such systems can be combined with other heat sources, for example, air pump heat source, water pump heat source and waste heat from incinerator/crematorium.

To achieve a full sustainability goal and build better sustainable cities, organisations should work together to formulate strategies to utilise all the untapped resources available around us. Although brownfield is regarded as only a small part of development issues, sustainably utilising the resource will act as a catalyst in solving other bigger issues. This can be achieved with the creation of formal regulations on the diversification of brownfield development purposes. This research has established that group consensus can be achieved through workshops to identify suitable sites to be developed where decisions can be made more conveniently.

The policy review in Chapters 2, 3 and 4 provided vital information regarding brownfield, RE and RH and how their implementation can be boosted altogether. This addressed the second research objective to understand and analyse public policy related to brownfield redevelopment, RE and RH advancement.

9.8 Summary

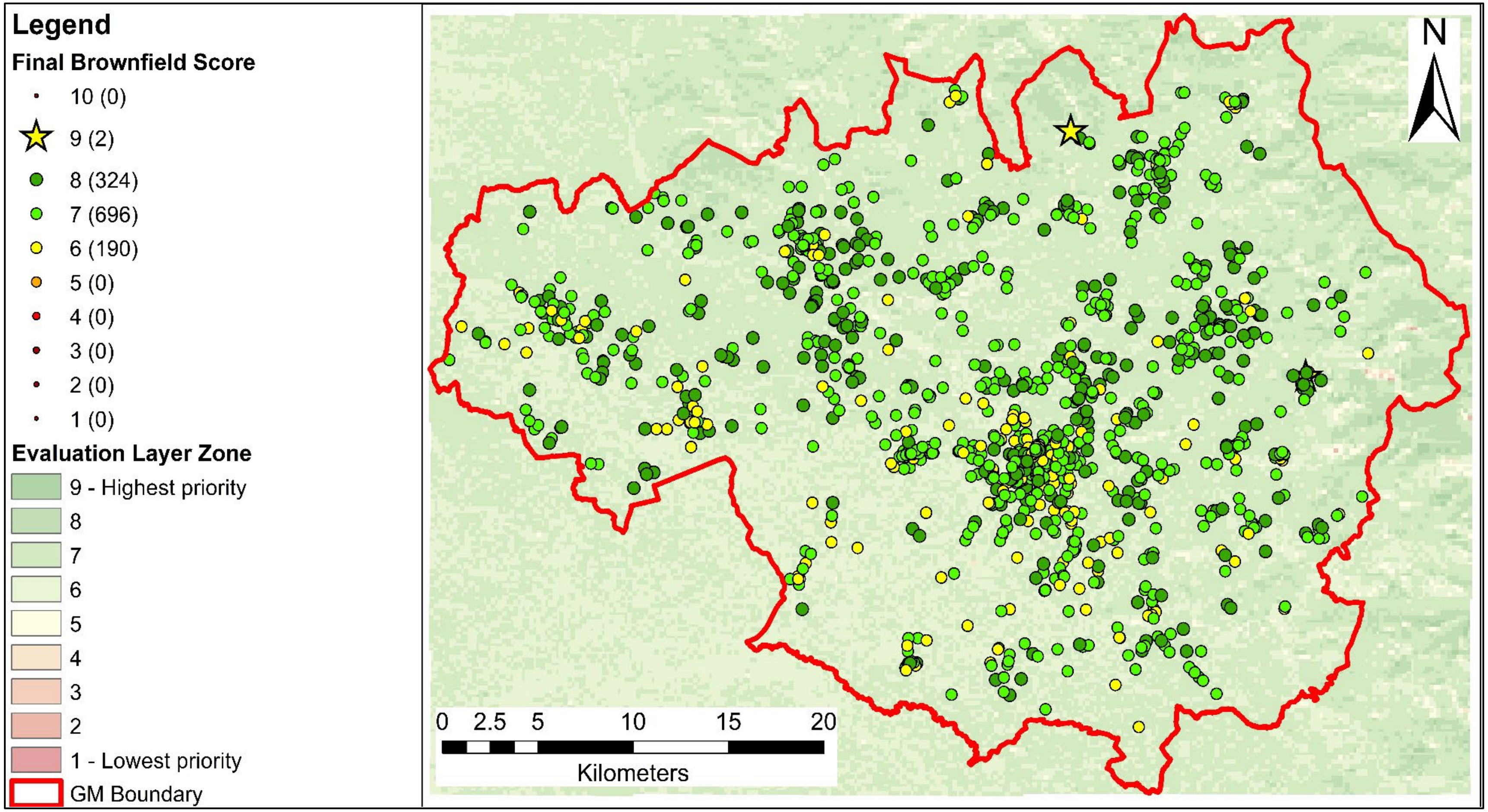
This chapter presented the prioritisation of brownfield sites for solar PV and WT installation employing various sets of criteria weightings. The results were accompanied by assessments explaining the outcomes. For the GSHP site selection, all brownfield sites were considered as feasible based on the discussion in Chapter 4; hence the sites were prioritised based on the two criteria (residential population and bedrock thermal conductivity).

It can be summarised that placing the highest importance/weighting on solar radiation/wind speed does not necessarily yield the best result with the most site count in the highest evaluation score. Likewise, the lowest importance assigned to flood zone/slope does not guarantee the best result, but there needs to be a balance in the criteria weighting as well as intervals of the scores.

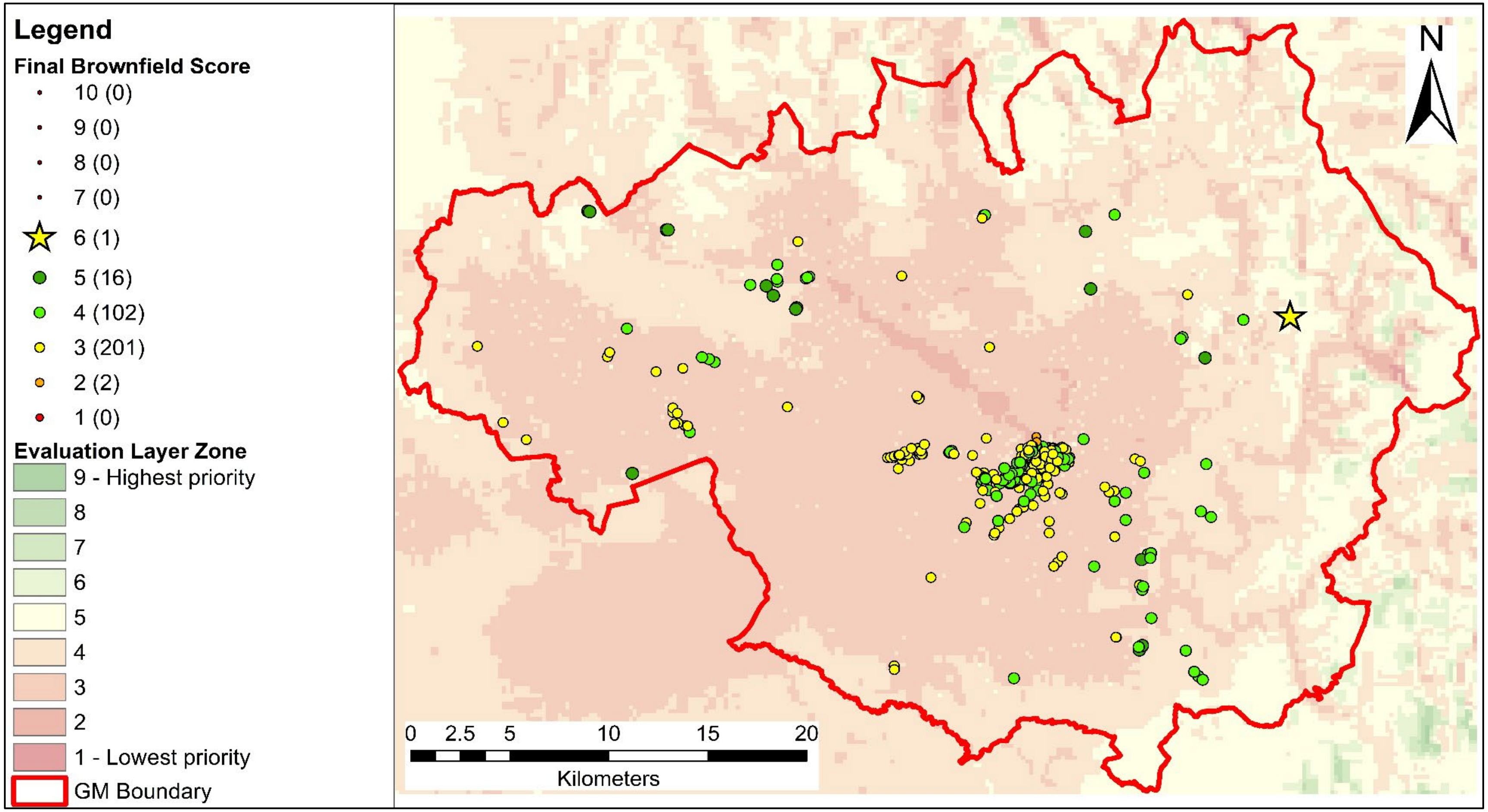
It is also important to analyse the site prioritisation from different scales to determine the best scale to be used. In AHP-OS, the best scale to be used for solar PV and WT installation is the Inverse Linear scale based on the analysis performed in this research. The scale can be adopted in other research and development project to ensure a lower dispersed set of weightings and a lower consistency ratio.

A deeper discussion was also conducted as an assessment for all the spatial analysis steps, MCDM method and workshop, criteria weightings and how future policy can be formulated, recapping what was achieved in each step and how the findings are beneficial for future planning projects. Chapter 10 elaborates the process of building a transferable process model for renewable energy planning, based on guidelines provided by the Department for Communities and Local Government and the methods adopted in this research.

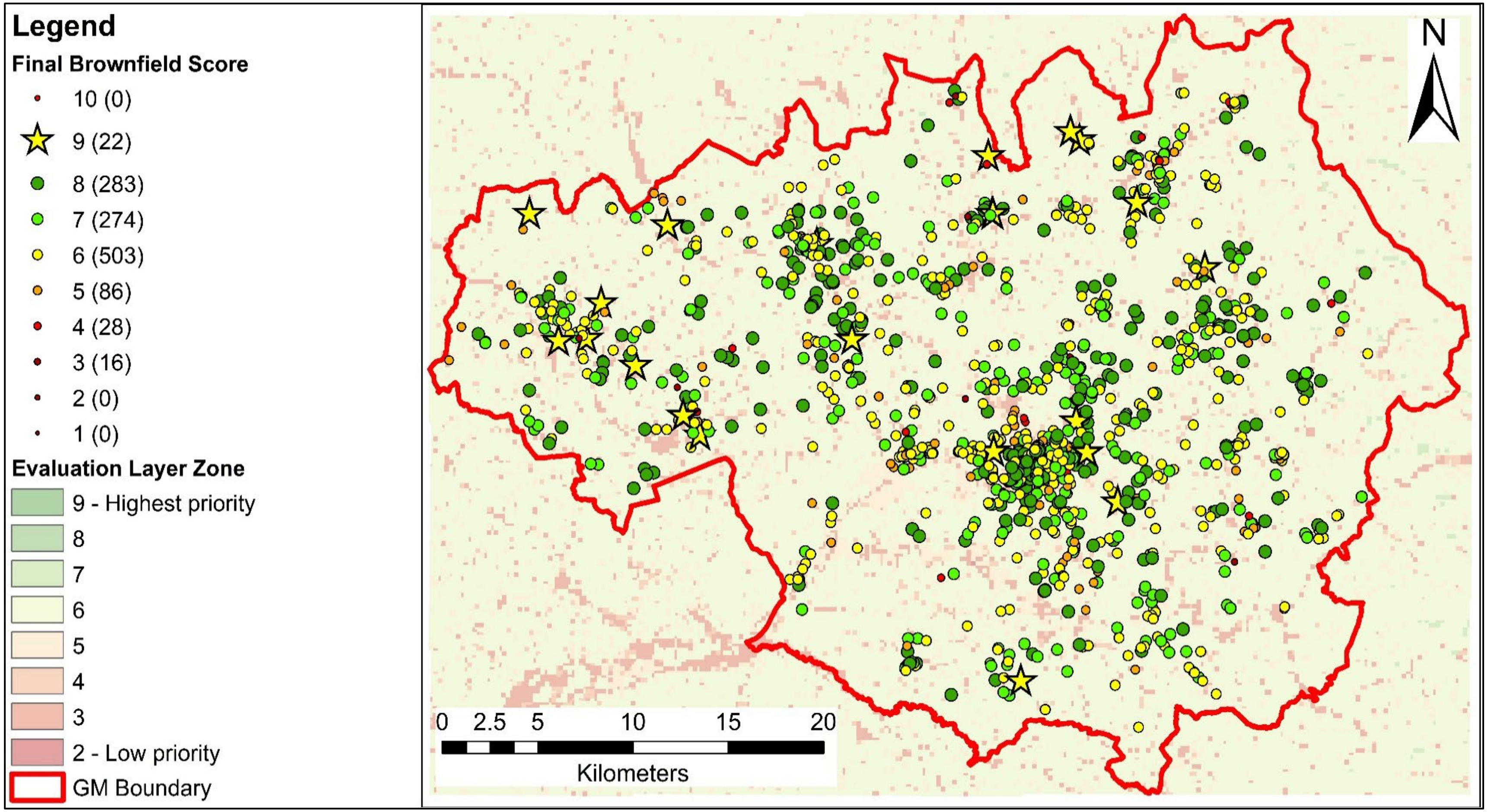
9.9 Maps



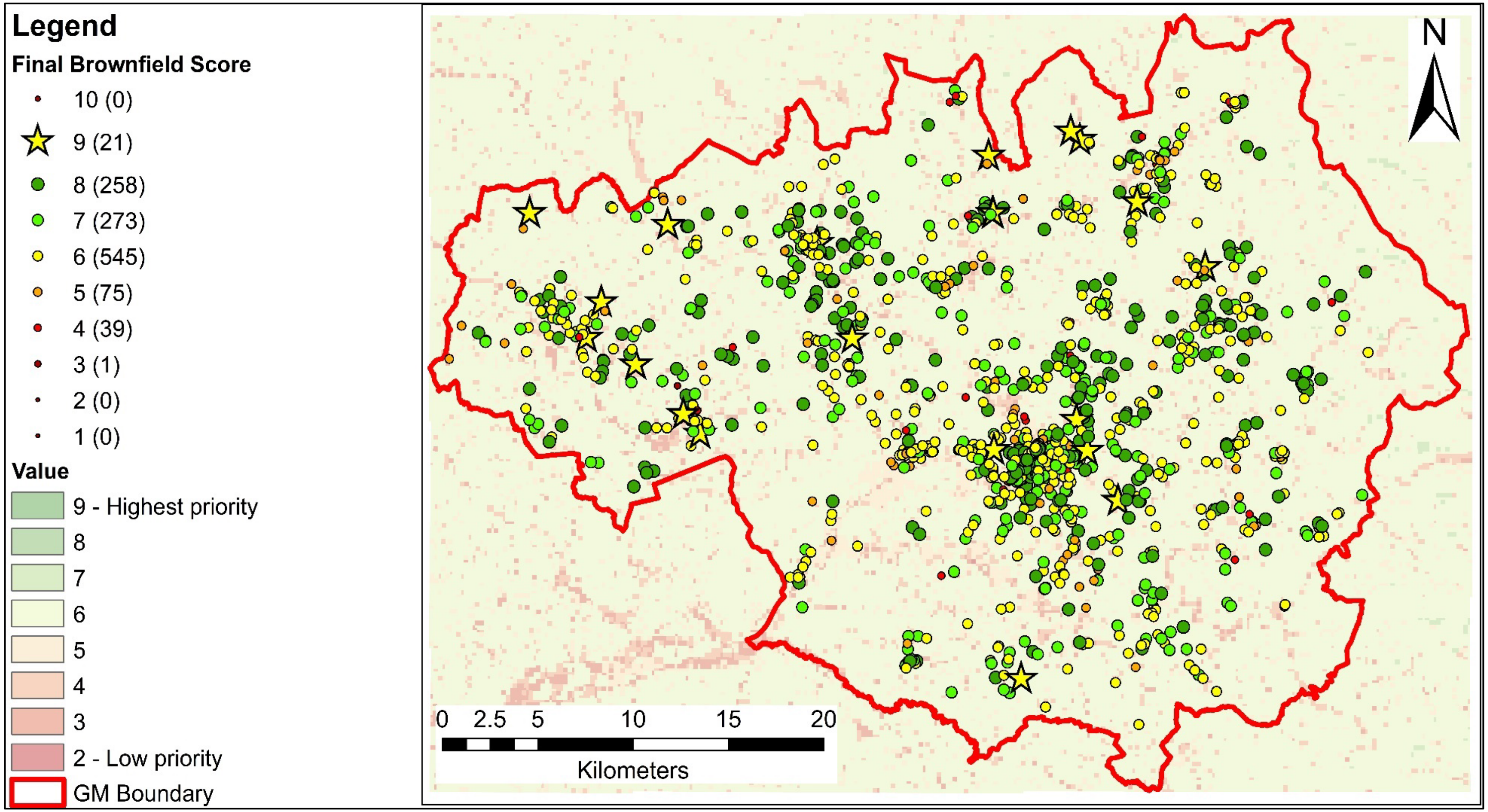
Map 9.5: Brownfield sites scored for solar PV installation using weightings deduced from Al-Garni & Awasthi (2017), Georgiou & Skarlatos (2016) and Carrión et al. (2008).



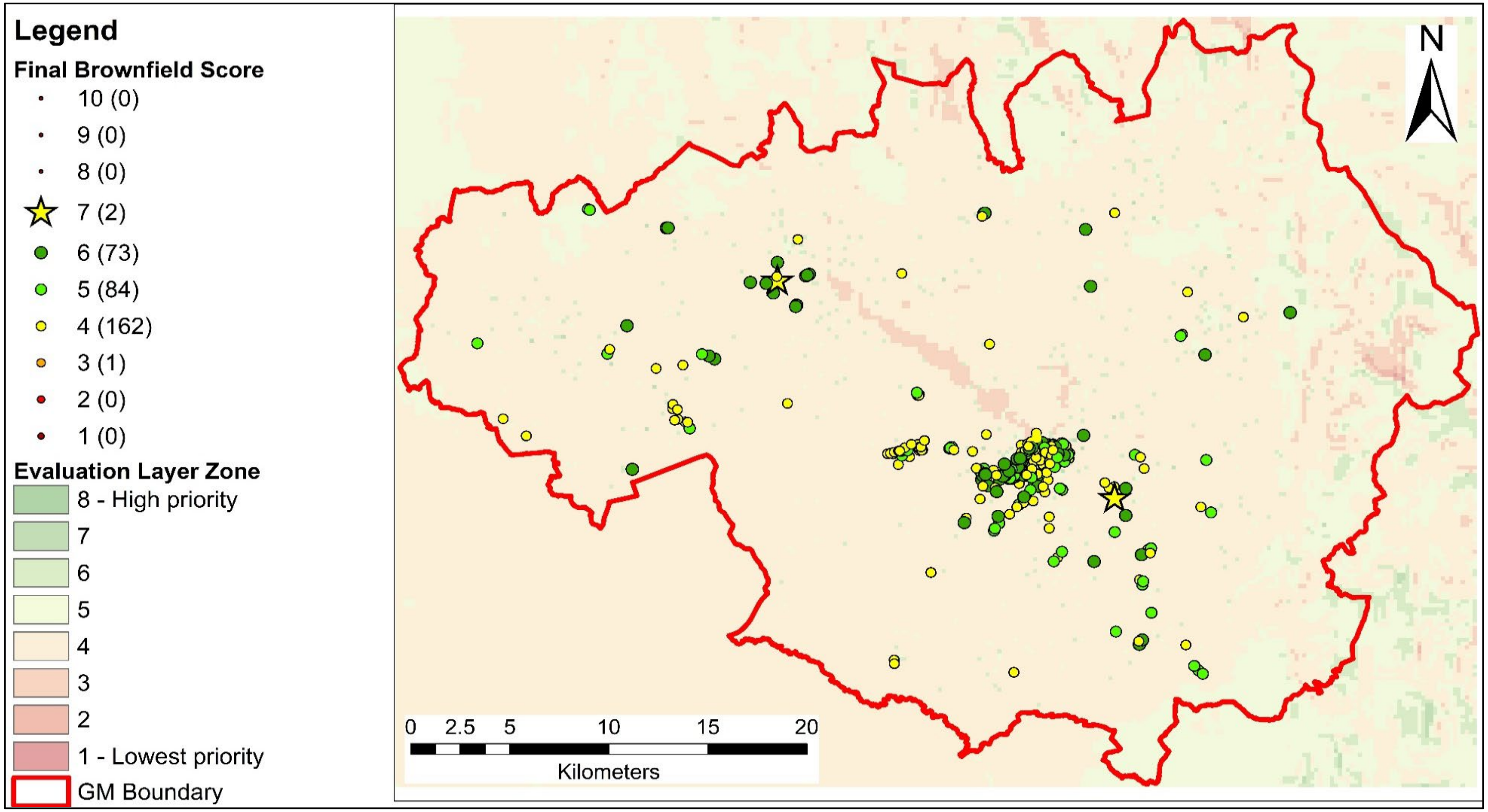
Map 9.6: Brownfield sites scored for WT installation using weightings deduced from Ayodele et al. (2018), Latinopoulos & Kechagia (2015), Neufville (2013) and Tegou et al. (2010).



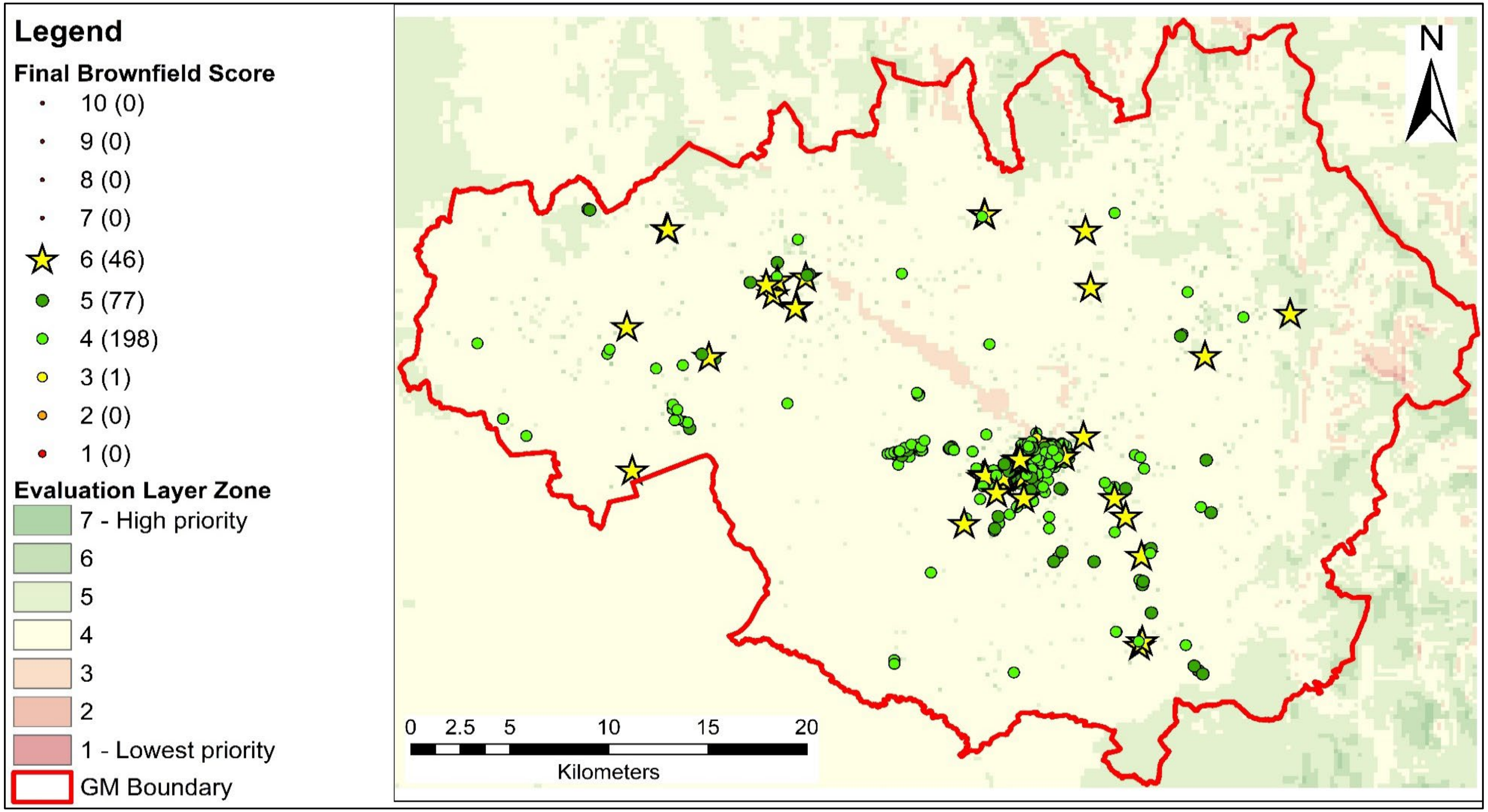
Map 9.7: Result for solar PV installation using MCDM workshop weightings and Inverse Linear scale.



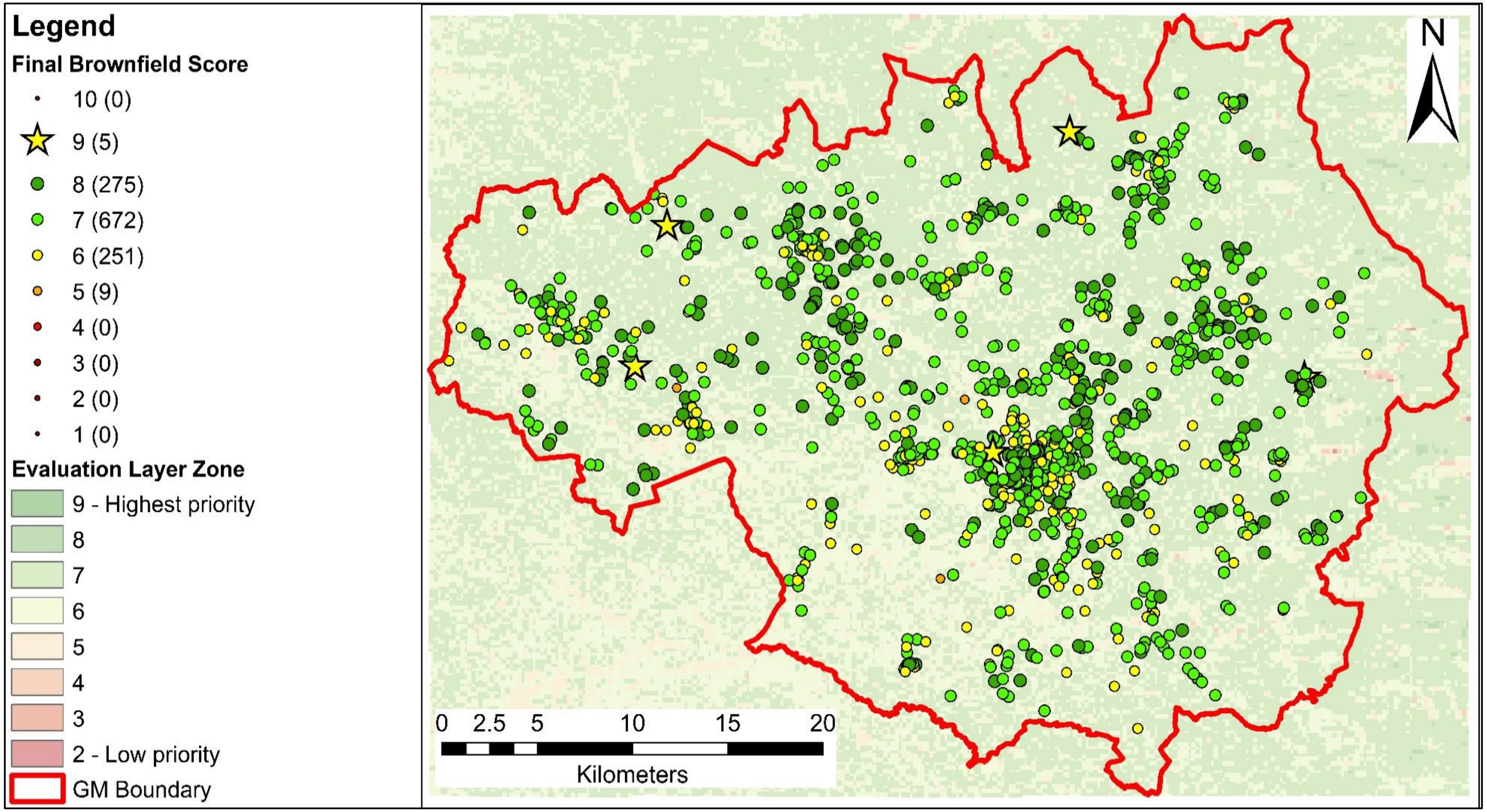
Map 9.8: Result for solar PV installation using MCDM workshop weightings and Balanced scale.



Map 9.9: Result for WT installation using MCDM workshop weightings and Inverse Linear scale.



Map 9.10: Result for WT installation using MCDM workshop weightings and Balanced scale.



Map 9.11: Scored brownfield sites for Scenario 1 of solar PV.

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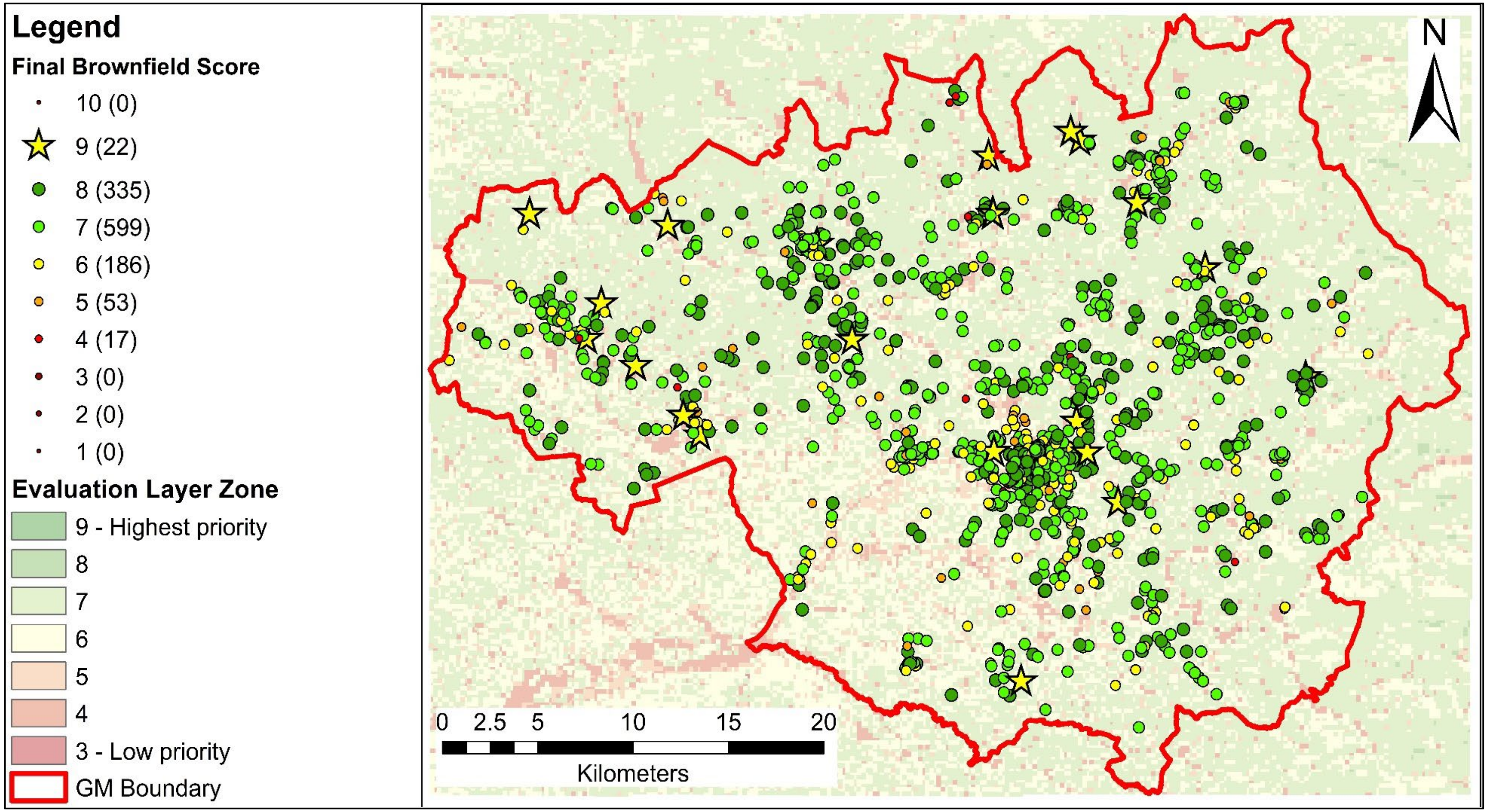
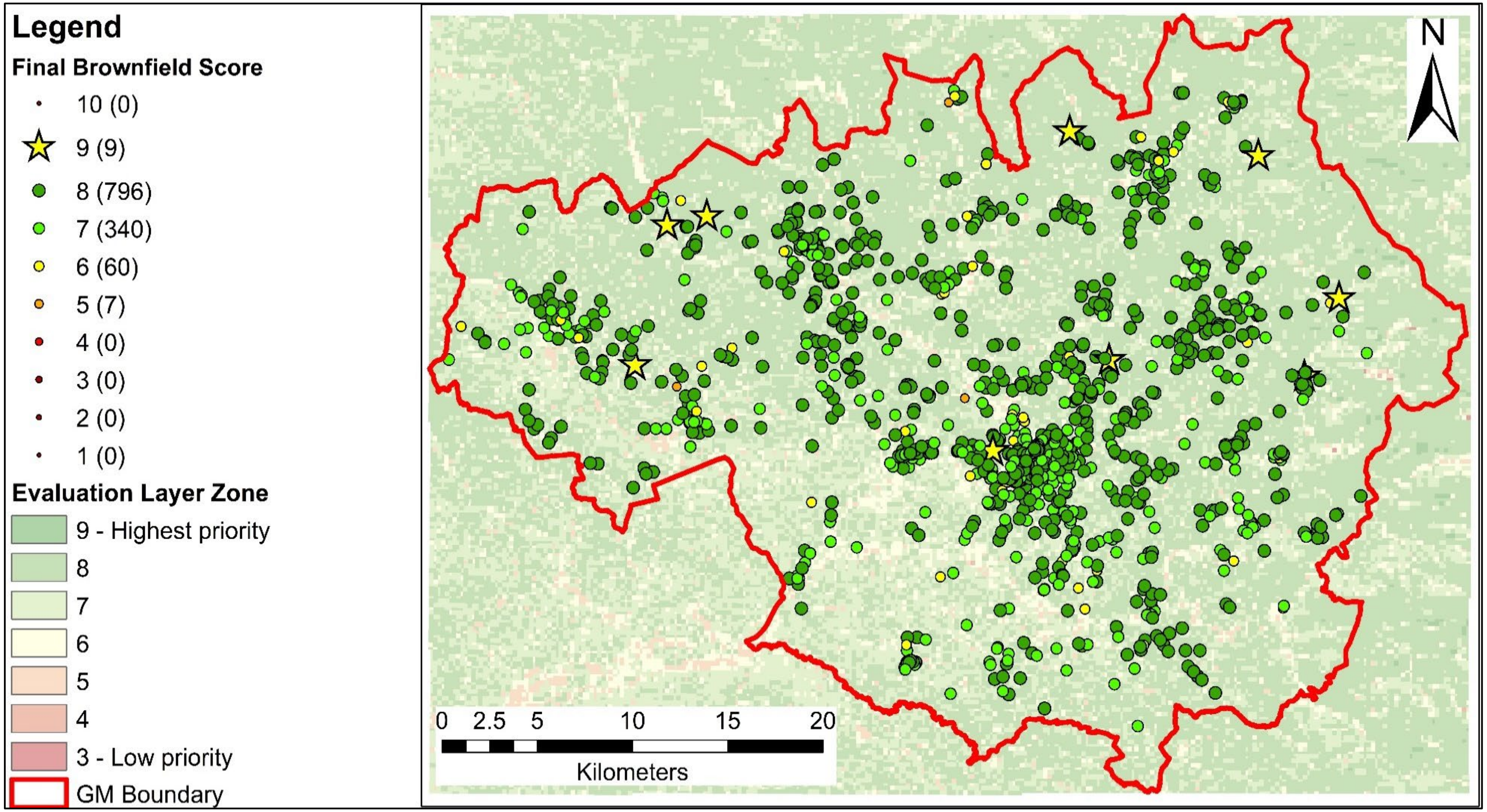
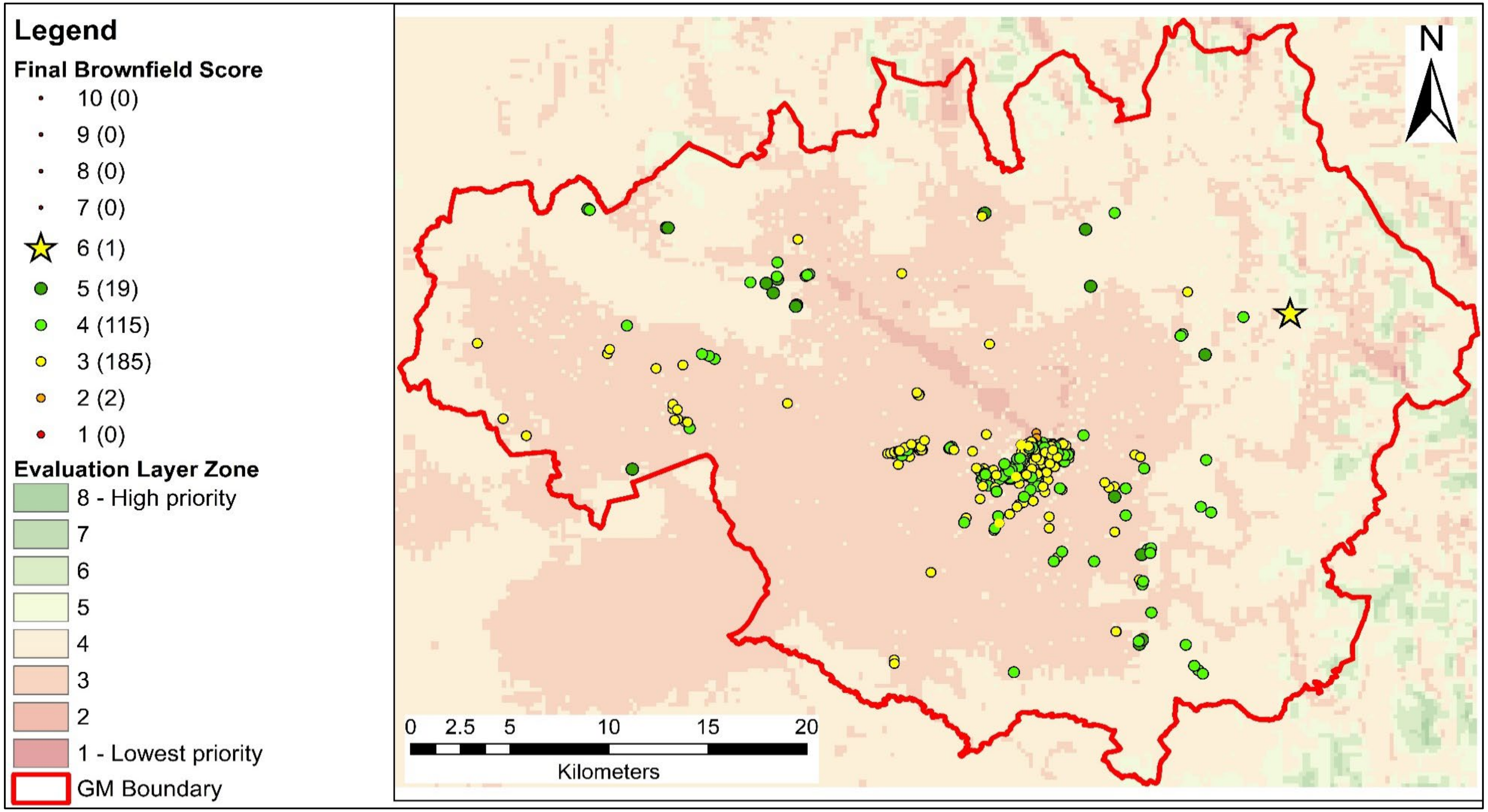


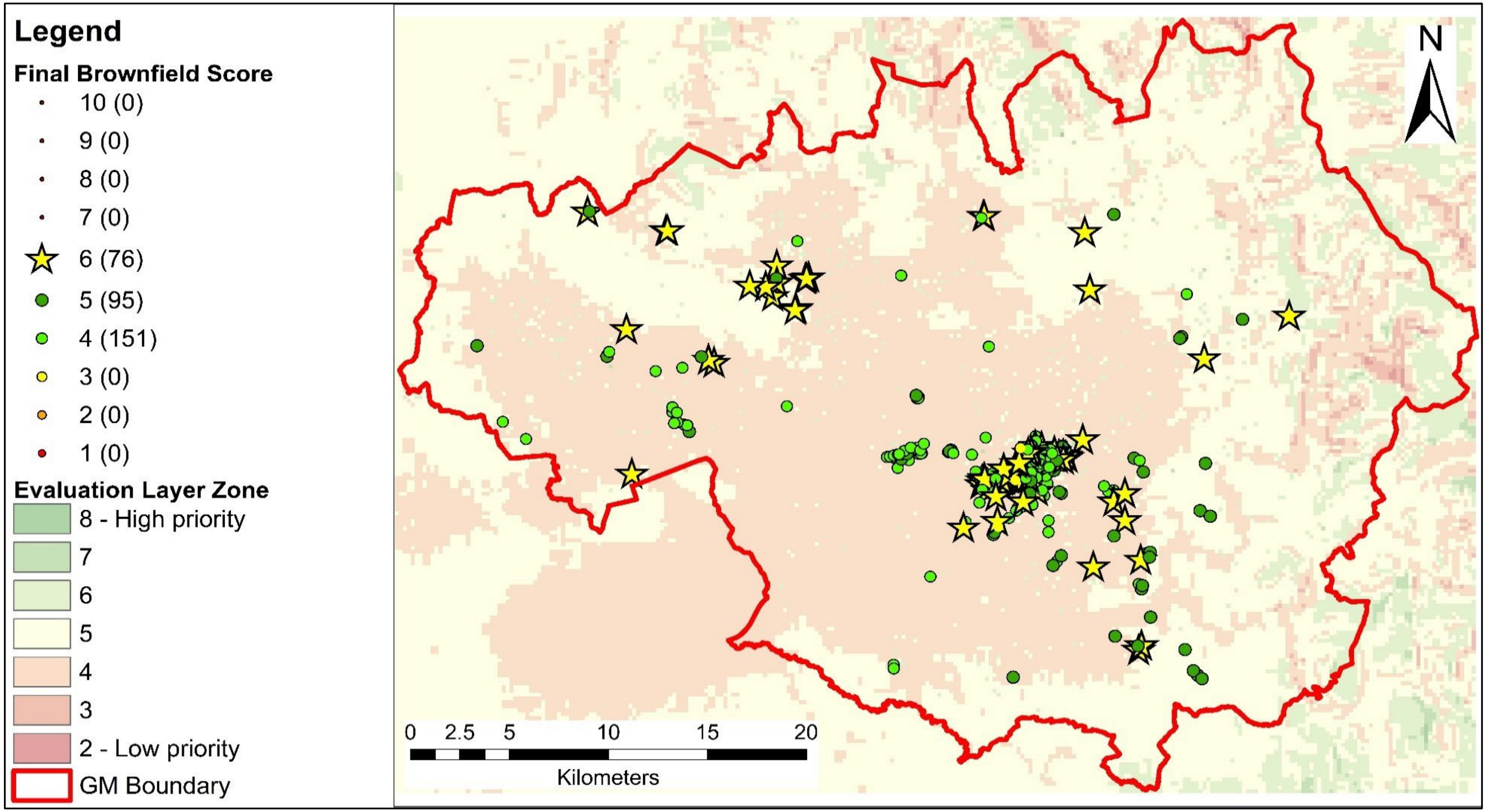
Map 9.12: Scored brownfield sites for Scenario 2 of solar PV; identical weightings for flood zone and site size.



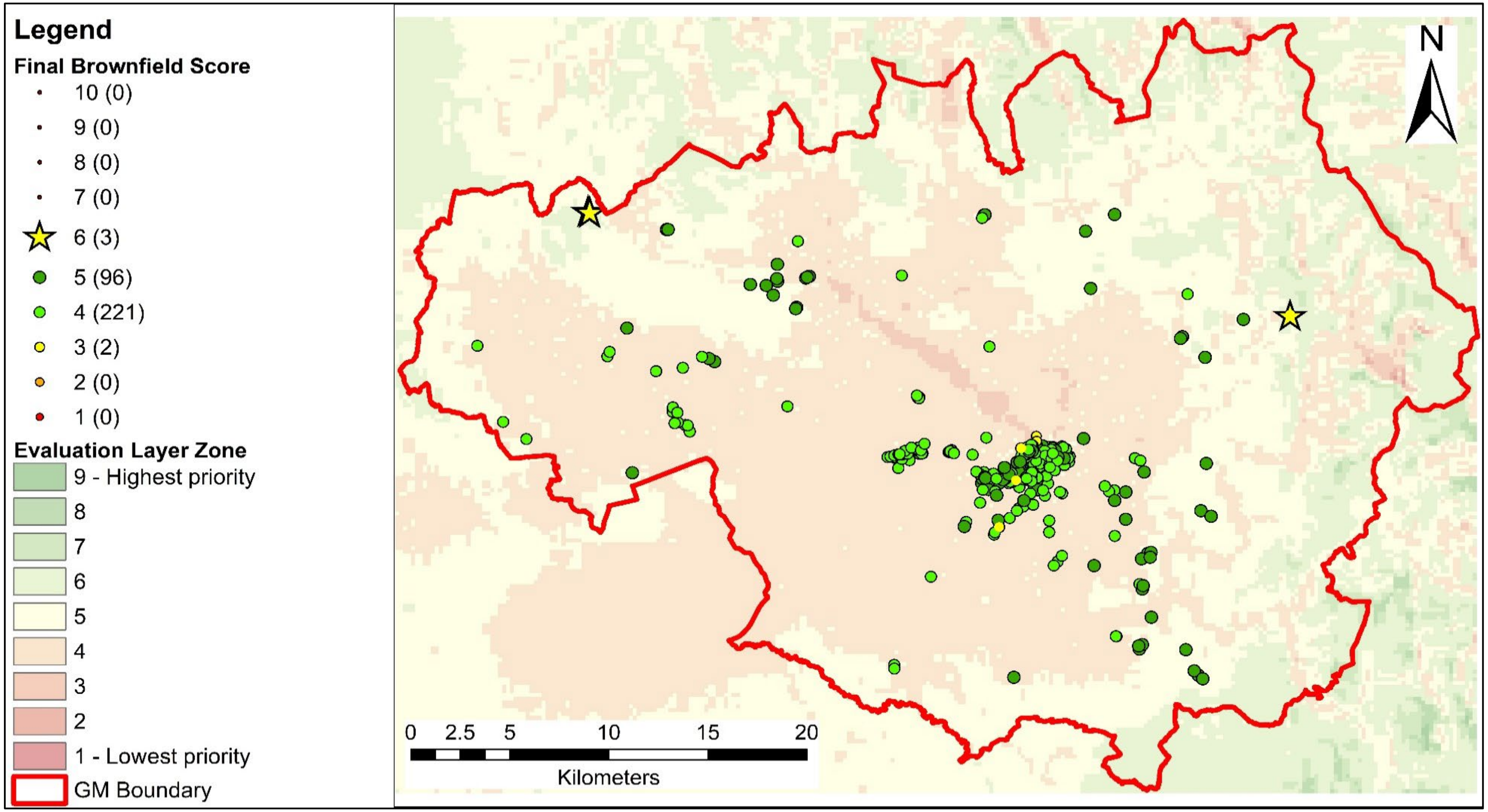
Map 9.13: Score brownfield sites for Scenario 3 of solar PV; flood zone has a higher weighting than site size.



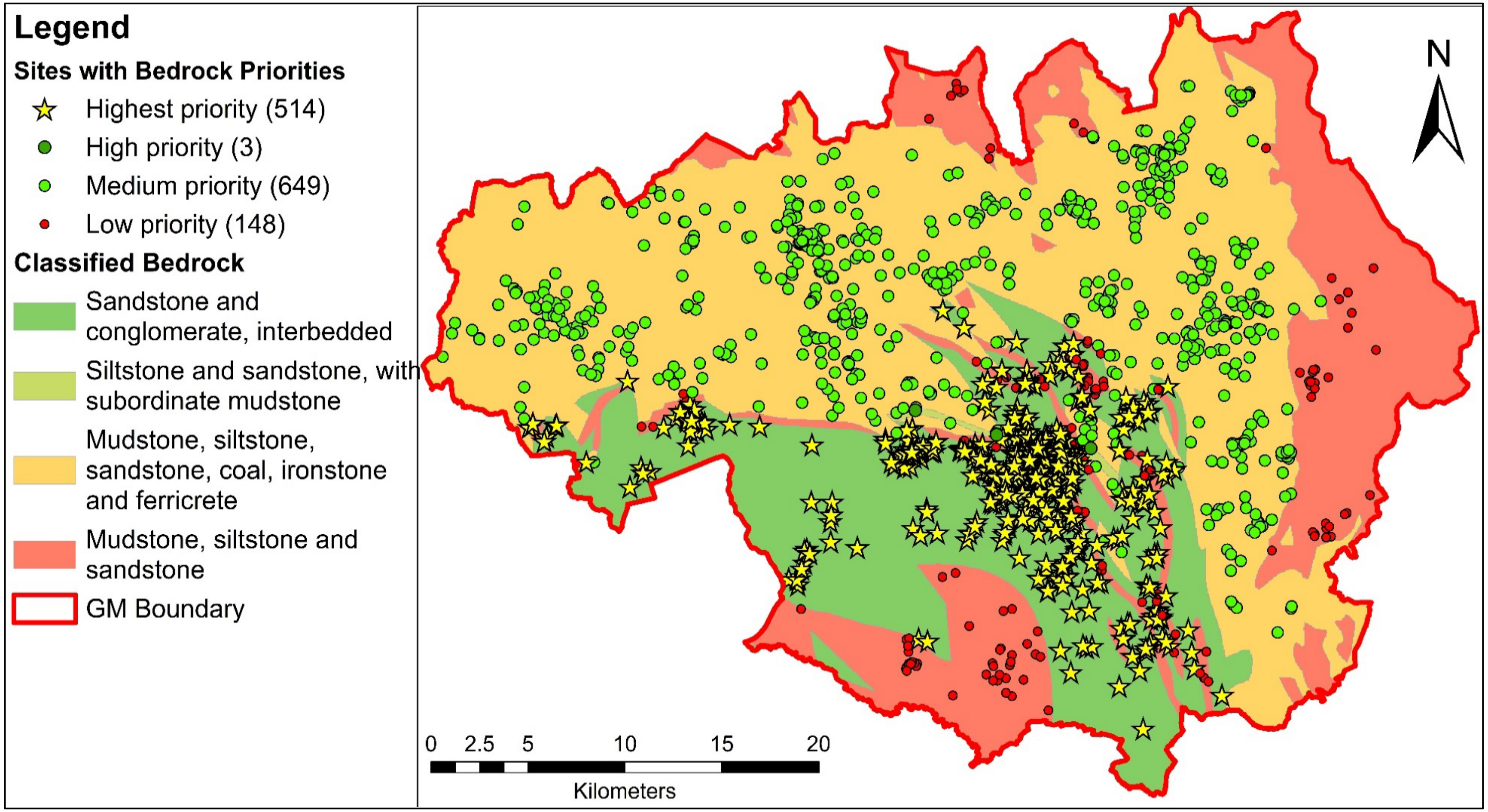
Map 9.14: Scored brownfield sites for Scenario 1 of WT installation.



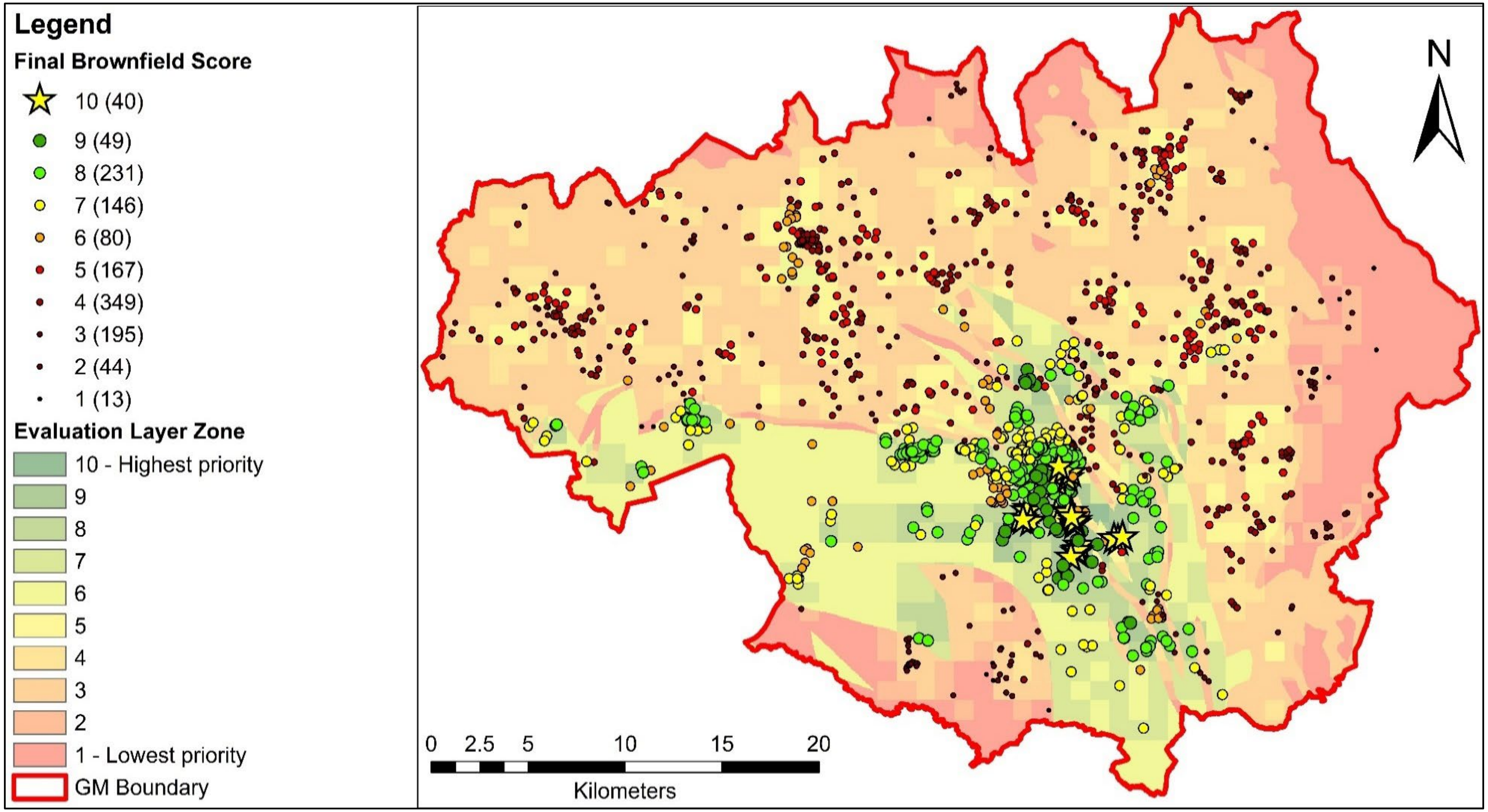
Map 9.15: Scored brownfield sites for Scenario 2 of WT installation. Slope and site size have identical weightings.



Map 9.16: Scored brownfield sites for Scenario 3 of WT installation.



Map 9.17: Brownfield locations according to bedrock thermal conductivity levels as tabulated in Table 9.9.



Map 9.18: Sites prioritised for borehole GSHP, accounting for bedrock and residential population density.

Chapter 10 : Transferable Process Model for Renewable Energy Planning – A Step to Sustainable City

10.1 Introduction

In this chapter, a combined process model is proposed for future renewable energy (RE) site identification. This builds on the discussion of guidelines provided by the Department for Communities and Local Government (DCLG) in identifying suitable sites (sections 7.3 through 7.5.6) and techniques applied in this research (Chapter 6). The creation of a combined process model addressed the final objective of this research to support the implementation of RE and brownfield development in other cities/countries and contribute to building sustainable cities.

This chapter discusses the guidelines provided by DCLG step by step in identifying suitable sites for RE and renewable heat (RH) installations. The methods adopted in this research are then reviewed to amalgamate the techniques with the guidelines provided. The combined processes are subsequently discussed and illustrated in Figure 10.3 to ease understanding. The final section then transfers the whole process into a timeline plot with the number of participants and items involved, this helps with the execution of site identification and logistics in future projects.

10.2 The DCLG Guidance for Site Identification for RE Installations

In future sustainable city projects involving other types of renewable technology, the technology to be implemented can be set in the initial step of goal and objectives setting, which is often part of an organisation's goal. A guidance document produced by the UK government through the Department for Communities and Local Government (DCLG) provided 31 general guidelines on the site identification process for RE and low carbon technology installations. The guidelines provided by DCLG were chosen as they were general and applicable to the Greater Manchester context. They can also be adopted in other locations where feasible.

There are no hard rules on how feasible areas for RE should be identified, but as a foundation, the consideration for suitable areas should take into account the range of technology and the technology capacity (DCLG, 2015; DCLG, 2013, p. 4). This can be interpreted as identifying the appropriate type of renewable technology that can be installed and the capacity of the technology as different capacities require different levels of planning permission and approval (DCLG, 2015;

DCLG, 2013, p. 3). It is also important to identify the capacity to be installed as it will have a direct correlation with the space required. In this research, due to many brownfield sites in the region having potential for RE development, various installation capacities could be considered. As such, a specific capacity for each technology was not considered early on, as it could depend on the site size and if there was any existing infrastructure.

The document also emphasised the impacts that the technology has on the environment, necessitating the impact assessment, including the physical impacts the technology would have such as the placement of wind turbines that can interfere with the aviation system or bird migration path, and the visual impact that RE sites would have on heritage and protected sites and surrounding neighbourhoods (DCLG, 2015; DCLG, 2013, pp. 3-6). Impact assessments can use tools to identify where impacts are likely to be acceptable. However, in some site identification studies for RE, visual impacts were not considered at a regional level as it requires thorough observation and scrutinization at a site level (Sánchez-Lozano, et al., 2016; Noorollahi, et al., 2016a; Sánchez-Lozano, et al., 2015). The impact assessment should be done at a site level to minimise or mitigate the impact of RE deployment. As executed in Chapter 7 of this research, the technological impact was assessed for wind farm identification to avoid interference with the airport area and protected areas at a regional level. Whereas for solar PV installations, urban areas were not excluded due to their potential at supplying locally generated energy and previous installations in conurbations.

When identifying potential RE sites, the DCLG document suggested considering the technical requirements (DCLG, 2015; DCLG, 2013, pp. 5, 10). This can be interpreted as the general requirements needed to install any particular RE technology or the location requirements. Technical requirements include site size, aspect and slope. These form a vital foundation of site identification as these criteria determine the feasibility of installation at the site. Exemplified in Chapter 7 of this research, technical criteria were considered for the solar PV, wind turbines and GSHP installations, acknowledging their available sizes, how brownfield land can accommodate them and installation types for different technologies sizes.

Besides the technical requirements related to the installation of RE, technology-specific considerations such as wind speed, wind direction, solar radiation level and thermal conductivity should also be given attention (DCLG, 2015; DCLG, 2013, p. 8). Wind speed and wind direction are only applicable to wind turbine installations, whereas solar radiation level is only relevant for solar PV deployments. The consideration of these criteria is to ensure an optimum output is obtained from the RE system while also bringing profit to the investment. This step was incorporated in this research in Chapter 7 where technology-specific criteria were assessed separately for solar PV, wind turbines and GSHP due to their different functionalities.

In conjunction with identifying suitable sites for RE and low carbon technologies, DCLG suggested discussing with experts that can help to identify siting requirements and potential impacts of technologies (DCLG, 2015; DCLG, 2013, p. 5). More specifically, discussion with experts can narrow down the sites to be chosen for RE deployment. Although this may be an optional step provided by the guidance and experts do not need to be involved in all projects, there is likely to be a difference in the decision made by groups of non-experts (DCLG, 2009). In this research, experts were invited to contribute their knowledge in the weighting process that formed the main part of the site identification. The significance of their involvement is explained in sections 6.8, 6.9 and 10.4.6.

The government guidance also recommended consulting local communities where RE technologies are to be installed to ensure any issues or objectives relating to the installations are addressed (DCLG, 2015; DCLG, 2013, p. 4). These can include noise produced by wind turbines, any noise resulting from the construction process and inconveniences to the traffic. It is also important for the planned project to be supported by affected communities in the neighbourhood. Besides addressing any issues that may arise from the project, the consultation with the local communities can also increase their awareness of RE. For instance, in section 4.4, the usage of GSHP was observed to be quite low in certain areas due to the lack of public awareness of the system. By involving local communities in the early stage of the project, awareness can be raised, issues can be addressed and subsequently better sustainable cities can be built. Figure 10.1 compiles the components in the guidance by DCLG (2015). Due to the broad evaluation of sites in this research, local communities were not consulted as it was considered more appropriate when evaluating specific sites to address issues impacting communities.

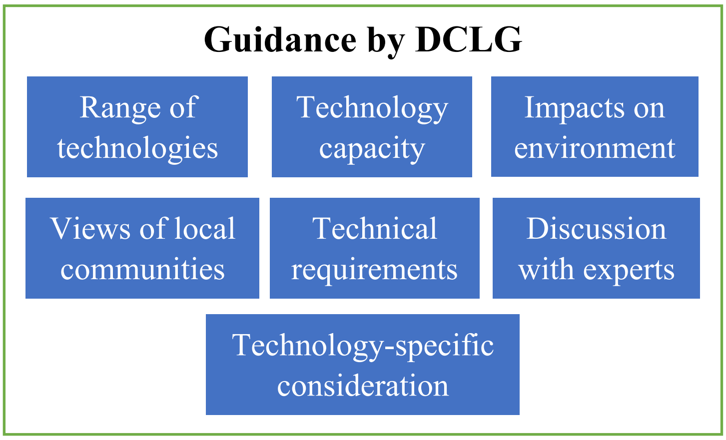


Figure 10.1: Components in the guidance for RE and low carbon technology siting (DCLG, 2015).

10.3 Site Identification Techniques Applied in Research

This research executed a site identification process based on the MCDM process utilising AHP in determining the criteria weighting for solar and wind farms. The adoption of MCDM in the process was due to the non-monetary criteria considered in identifying suitable brownfield sites, outlined in Chapters 6 and 7. The process began with setting the objective and identifying the appropriate technology to be installed. Relevant criteria were selected based on a literature review for application at brownfield sites in Greater Manchester.

Data for the relevant criteria were acquired and studied before they were classified into restriction and evaluation. Restriction criteria simply applied a binary principle in the GIS analysis, where 0 indicated unfeasible areas and 1 indicated feasible. Evaluation criteria were rated in intervals and weighted by experts through an MCDM workshop. This was to assign appropriate influence on the criteria.

GIS analysis was then conducted combining the restriction and evaluation criteria and weightings obtained to compute brownfield suitability scores for solar PV and WT deployment. High scores were obtained for sites that received higher ratings and were more favoured for development. Brownfield sites were mapped according to their scores and locations to ease assessment. Figure 10.2 simplifies the techniques applied in the project to consider for the proposed process model for RE site identification.

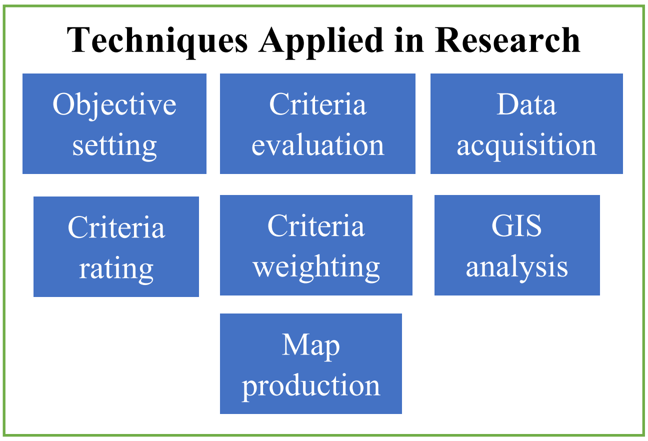


Figure 10.2: Site identification techniques applied in this research.

10.4 Proposed Process Model for RE Installations at Brownfield Sites

The techniques applied in this research concentrated on the feasibility of the site according to the specified technology. However, there were similarities in the techniques applied with the guidance provided by DCLG, although there were no specific criteria and values set in the guidance. To support

RE and low carbon technology installations in other geographical contexts, the guidance from DCLG is amalgamated with the techniques applied in this research.

Sections 10.4.1 to 10.4.8 describe the individual steps in the proposed model, followed by the illustration of the integrated steps in Figure 10.3. In this figure, brownfield development, criteria rating and criteria weighting stages are indicated with a dashed outline to signify modifiable parameters. This means the data or consideration can be altered and will change the final site suitability scores in the GIS analysis. The criteria to be considered for the respective technology will also change, corresponding to their relevance to the location and project. However, the overall processes can still be adopted in terms of data acquisition, experts' involvement and GIS analysis.

10.4.1 Choosing the Right RE Type

The first step to identify suitable areas for RE installations is to choose the right type of RE. This was recommended by DCLG in their guidance as 'to determine the range of technology and capacity' (DCLG, 2013). As explained in section 10.3, this step was reflected in the objective setting step, where the type of technology was determined for the goal set, as set out in Chapters 3 and 4. Alongside the technology, it is also beneficial to consider policies relating to renewable technologies, both renewable energy and heat as they can determine what type of technologies and what capacity would be more appropriate to deploy.

The consideration of technology can also include the 'accessory' to boost the energy output, for example, a solar tracker can be used with solar PV to track sun direction throughout the day, a concentration tower can be used to build concentrated solar power or a higher mast can be installed for wind turbines to capture more wind. This consideration can be integrated into the preliminary consideration or later at the site level as a mitigation measure if a site with lower priority is to be developed.

10.4.2 Integrating Brownfield Development into RE Installation

The second step in the combined process is to consider brownfield development. As suggested by DCLG 'to consider and mitigate the impacts on the environment' (DCLG, 2015; DCLG, 2013, pp. 8-10), this research focused on brownfield regeneration as a step to contribute to sustainable city. The development of brownfield for RE is highly advantageous due to the conditions of brownfield sites that have previously been developed, located near substations/grid lines and near to energy demand as discussed in Chapter 2. Policies applicable to brownfield regeneration should also be examined by project executors to evaluate the eligibility of the project for initiatives or aids that can boost the development further.

Besides the applicable policies, brownfield site size is also to be assessed. This is key to identifying the types of technology and their installable capacities at available sites. Integration of brownfield sites should be conducted using spatial data to narrow down the sustainable city scope, instead of identifying other types of land. Where possible, the brownfield contamination level should also be assessed to determine the appropriate installation method that can affect associated costs. In other cases where different types of land are to be developed, similar steps and assessment can be conducted using relevant data corresponding to the type of land. This modifiable parameter is indicated with a dashed line in Figure 10.3.

10.4.3 Evaluating Criteria for Relevance to Technological and Geographical Context

The criteria evaluation follows to select relevant criteria for consideration. Due to differing criteria applicable for different technology, this step requires specific knowledge on technology to be installed. The DCLG guidance (2013) recommended incorporating technical requirements and technology-specific consideration when selecting suitable RE sites. As exemplified in the Greater Manchester study, the criteria selection process in Chapter 7 justified relevant criteria incorporating brownfield conditions for the Greater Manchester context.

Criteria were initially extracted from the literature by comparing their purpose and values to avoid arbitrariness in criteria selection but adapted accordingly to fit the context of the study. The technical requirements such as aspect and slope and technology-specific requirements such as solar radiation level and wind speed were accounted for to find optimum sites. Such considerations should also be made as an essential step in other brownfield development planning for RE to ensure optimum energy output.

10.4.4 Relevant Criteria Acquisition

Upon setting suitable criteria for RE installation in the right geographical context, their spatial data are needed to enable the subsequent stage of site identification. These data can be obtained either from government sources, organisational datasets or generated using GIS software, for instance, aspect and solar radiation data. The criteria are categorised as either restriction or evaluation. For restriction criteria, different values indicate feasibility, whereas, for evaluation criteria, they indicate preferability. Restriction criteria can be fed straight into the GIS database for analysis once their feasible/unfeasible values are set, but evaluation criteria need to be linearized or assigned proper intervals and rated before they can be applied.

Some data might have slight discrepancies in their values due to different computation methods, average values or other reasons. Users should be mindful when choosing the right numerical data and considering the right type of data, for instance, wind speed vs wind density or urban population vs urban density. Regarding non-numeric data such as protected areas, heritage areas or Ramsar sites, their data can be obtained from governing organisations' websites. Data that are used to exclude certain areas from consideration or to impose a buffer zone are usually categorised as restriction, meaning they receive binary classification on the map. As discussed in Chapter 6, when a restriction area is identified and indicated as 0, the affected area will not be considered further in the evaluation process. Other criteria with numeric values are classified and rated to ease the GIS analysis that follows.

10.4.5 Criteria Rating

Evaluation criteria which are typically numerical need to be set in intervals and rated. This forms another modifiable parameter in the combined process, where internal values can be changed manually. Unlike the criteria selection that is dependent on the technology and location chosen, the values of these parameters determine the final suitability of sites to be developed. A lot of research used the interval values fed into the GIS database in a non-linear form, although some research categorised them linearly (discussed in sections 7.4 and 7.5). This highly depends on the values available for the data to be considered and the rating to be assigned for each value.

The criteria rating should be made in the same number of intervals. This is to avoid issues in the normalisation process and classification in the GIS analysis. Elaborated in Chapter 7, the skewing of criteria values is helpful in certain cases where a small number of values is combined to a reasonable group of intervals. If this is not done, there can be a very large number of intervals representing very low values in each class and yield an imbalance criteria class.

10.4.6 Criteria Weighting Using MCDM

The relevant evaluation criteria need to be weighted to determine the importance of each criterion to the development. This is the follow up of the technical consideration stipulated in the guidance by DCLG. As conducted in much previous research involving MCDM (Sánchez-Lozano, et al., 2016; 2015; Noorollahi, et al., 2016a; Neufville, 2013), the criteria weightings in this research were obtained through a workshop participated by experts with knowledge on brownfield, chosen RE and location of study. DCLG (2013) recommended discussing with experts regarding the technology so they can provide the right information.

The experts' involvement in this research was highly valuable as they provided the right judgement on the preferred criteria for each technology. This was an important element of this research as the subjective judgement provided by experts prevented assigning arbitrary weightings in the spatial analysis that could lead to random brownfield scores and affect developments negatively.

As discussed in Chapter 6, many other MCDM methods can be applied in conjunction with GIS to identify suitable sites for development. AHP was adopted in the criteria weighting process due to its convenience of use, ease of understanding, availability as an online-based software and transparency of the method and software (Chapter 6). When compared to other MCDM methods, AHP evolves with many functions that can produce rational aggregated weightings despite being an old method. In future site identification projects considering non-monetary criteria, other MCDM methods may be a better option. It is worth noting that no one method can serve all purposes and contexts.

Regarding experts' involvement in the criteria weighting, future studies/projects have the option to involve stakeholders, local authorities or local communities in criteria weighting or evaluation, as conducted by Higgs et al. (2008) in promoting public participation in RE planning. By collaborating with stakeholders, local authorities or local communities, various non-technical criteria may have to be compromised since stakeholders do not usually share common goals to the same extent as members of an organisation do (De Brucker, et al., 2013). Nonetheless, when applying the right MCDM technique, the collaboration will be able to provide weightings for the spatial analysis. Their involvement is parallel with the recommendation by DCLG (2013) to have a 'discussion with experts' and take in 'view of local communities'.

When involving experts in other MCDM processes, the experts' contribution needs to be identified whether it is their subjective or objective knowledge. If subjective knowledge is used, then the method chosen needs to be able to ensure the consistency of judgement to yield a valid set of weightings. A consensus analysis might be beneficial to examine the aggregated weightings, as conducted in this research using AHP-OS.

10.4.7 Spatial Analysis Using GIS

The GIS analysis is the next step of the integrated process model. This integral part of the process is widely applied in various types of site identification studies, including nuclear power plant (Eluyemi, et al., 2020), landfill (Chabuk, et al., 2017; Demesouka, et al., 2016), medicine (Mohammadbeigi, et al., 2020), water storage (Ahmad & Verma, 2018) and architecture (Kang, 2020). Using GIS, various tasks can be executed using the functions available. DEM data can be converted into aspect and slope while solar radiation can be generated internally, all of which are needed for the site identification. This echoes the recommendation of DCLG (2013) to consider technology-specific criteria for RE siting.

As discussed in Chapter 5, many models are available to compute solar radiation levels producing different results. Users will be able to select suitable models that fit the purpose and location for solar radiation analysis. This will then determine which GIS software should be used as different models are embedded within different software packages. ModelBuilder, a plugin that compiles strings of workflows into a model is available within ArcGIS. This simplifies the process of site identification that involves multiple steps with complex intervals and values. Additionally, sensitivity analysis can be conducted easily for different weightings using ModelBuilder, explained in section 10.4.8. Maps will be produced in the final step once scores for all evaluated sites are computed, indicating highest to lowest preference for development.

10.4.8 Sensitivity Analysis

Sensitivity analysis can show different results using different weightings for any site identification study. Running this analysis enables project executors or decision makers to compare differences of site scores for different scenarios before finalising any decisions. This step can also reveal ways in which options can be improved (DCLG, 2009). As demonstrated in Chapter 9 (section 9.4), running sensitivity analyses using ArcGIS' ModelBuilder can help to integrate all values used in the process, including criteria values, ratings and weightings.

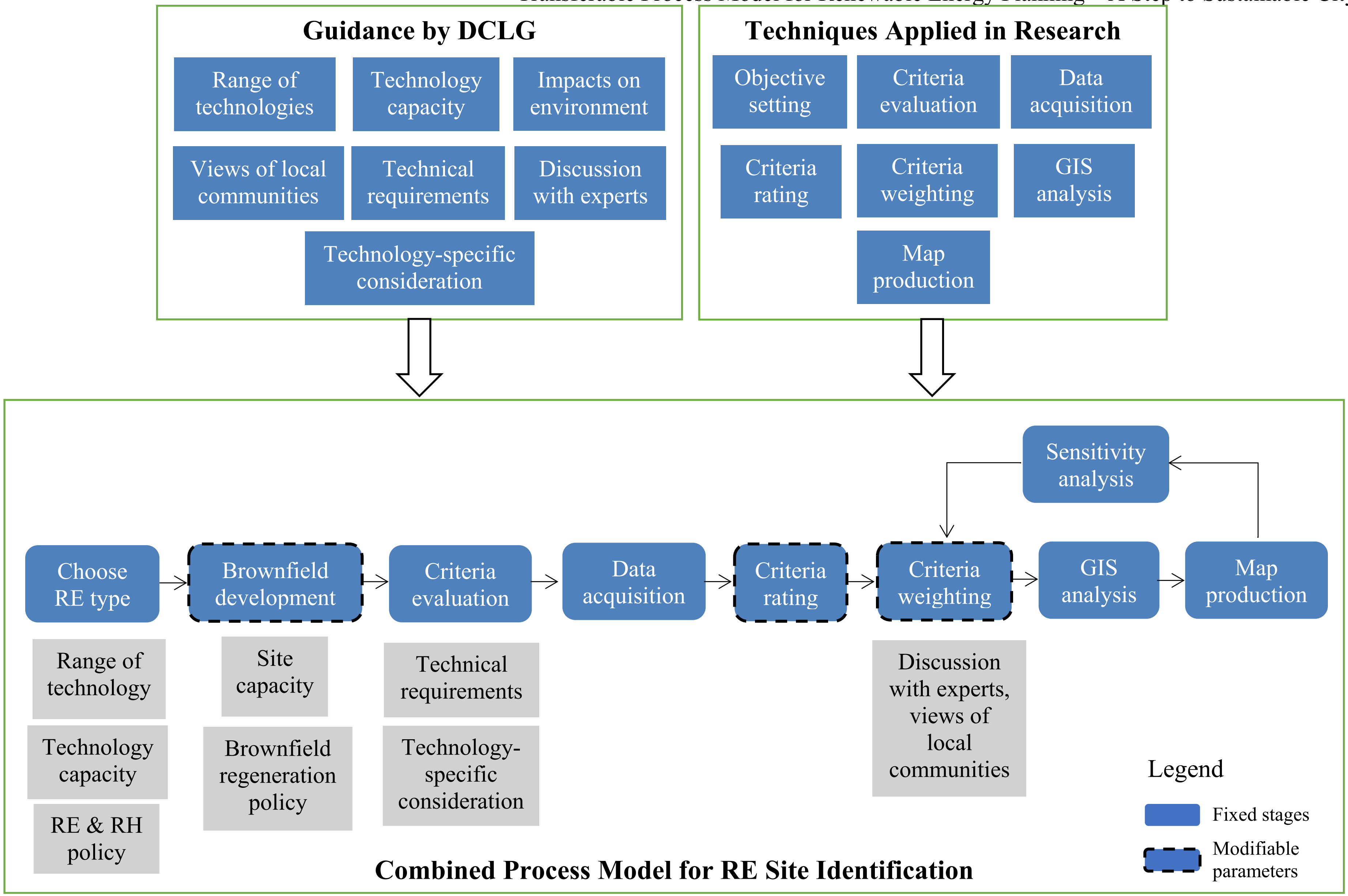


Figure 10.3: Process model for RE site identification, combining guidance from DCLG (2015) and steps executed in this research.

10.5 Transferability of the Process Model

The developed process model was based on the guidelines provided by DCLG in England. However, the applicability of the model is not only limited to the use in Greater Manchester, England or the UK but it can be adapted with suitable data. As the data used in the development were for the northern hemisphere (latitude 53°N), suitable adjustments need to be made to account for differences of the southern hemispheric conditions, for example, Australia and Argentina. Adjustments also need to be made when considering sites on the equator whereby solar PVs can be put flat for optimum energy generation instead of tilted.

Such adjustments can be made in the computation of solar radiation using GIS which takes into account the latitude of the location, suitable aspect for solar PV placement as considered in section 7.4.2 and the angle that solar PVs need to be tilted. This is because the latitude of the site affects the aspect and the tilting needed by the panels. Differences in the data and parameters taken into consideration can be reflected in the Choose RE type, Criteria evaluation and Data acquisition blocks of Figure 10.3. For WT, other criteria need to be examined if taken into account, as the difference in latitudes does not usually directly affect wind speed, slope or site size.

Once the adjustments are made in the values, classes can be assigned as conducted in this research, following the rating and weighting process shown in Figure 10.3. Experts can be involved in the weight elicitation process, as long as they understand the solar PV installation process. GIS analysis can be run to produce prioritised sites using relevant data.

10.6 Situating the Process Model Within A Timeline

The combined process model built upon the guidance by DCLG and the steps implemented in this research can be plotted in a timeline chart to illustrate the sequence, number of participants involved and associated tools/items applied (Figure 10.4). This chart helps in understanding beyond the sequence of the process to help with budgeting, participation and logistic planning for the project. With the indication of tools and items associated with each stage, project executors have a clearer vision of what is involved in the process and can make necessary preparation before executing a site identification project.

The number of participants for criteria evaluation and criteria rating stages is plotted in between to signify the possibility of having a small number of project executors or a larger involvement with experts to evaluate and rate the criteria. On the other hand, the criteria weighting stage is plotted at the highest number of participants to show the maximum possible participants that can be involved, particularly when involving local communities in weighting relevant criteria. The criteria weighting stage can however have smaller participation when only experts are involved, parallel to what was executed in this research.

10.7 Summary

This chapter discussed the guidelines provided by DCLG in identifying suitable sites for RE and low carbon installations. The guidelines mainly focused on deploying more RE anywhere in the UK without specific parameters set for criteria used for site selection. To supplement that, techniques implemented in this research, outlined in Chapters 6, 7 and 8 were integrated into the guidelines to create a process model that can be transferred to other RE planning. The integrated process model is aimed to contribute towards building sustainable cities while addressing the final objective of this research.

The process model adopted brownfield development, as executed in this research and recommended by DCLG (2015) and DCLG (2013) for any RE development. Using Greater Manchester as a study area to test the execution of the method, the final process model is generalised for application in other planning projects to achieve various goals and objectives. Users can tweak applicable values accordingly for the modifiable parameters. An emphasis is put on brownfield development to target the reuse of previously developed land and help curb the reliance on fossil fuels.

The integrated process illustrated in Figure 10.3 and Figure 10.4 provides an easy and adaptable model for the planning of sustainable city development which tends to be complex and lengthy. With the outcome of this research, site identification tasks for different goals and objectives can be performed using the MCDM method and GIS. Chapter 11 concludes with the summary of findings, key contributions, limitations and recommendations.

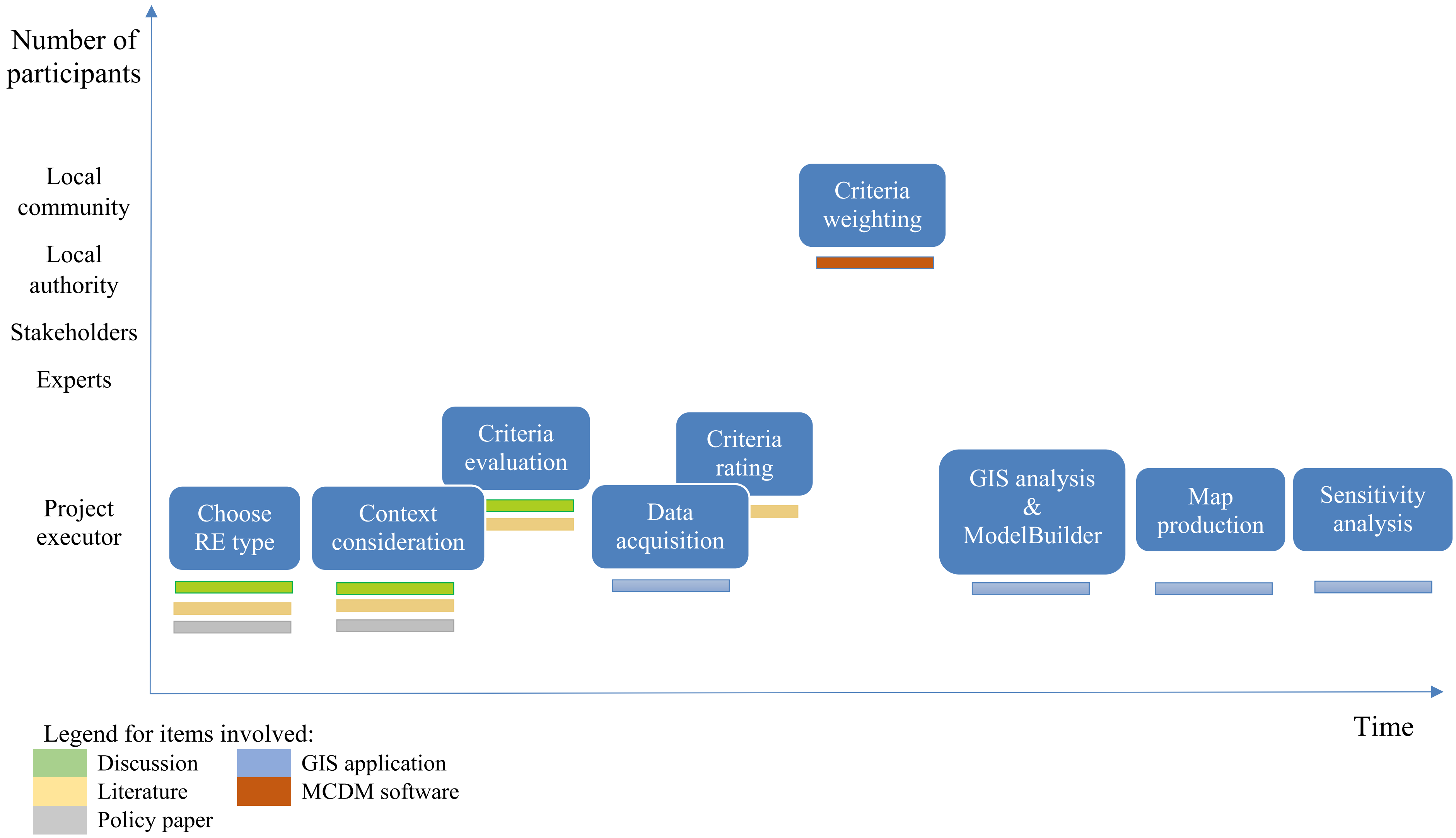


Figure 10.4: Site identification process model plotted against a timeline and the potential number of participants.

Chapter 11 :Conclusion and Recommendation

11.1 Introduction

This chapter begins by summarising the research findings and identifying key contributions. The chapter then highlights the novelty of this research and correlates that novelty with the overall project aims. From the findings and contributions, the chapter explains how the research objectives were achieved. It continues by outlining the limitations faced during this research project, before discussing potential future research. Finally, recommendations are made to enhance the siting of renewable energy (RE) and contribute to sustainable cities.

11.2 Summary of Research Findings

Chapter 2 established various ways to redevelop brownfield land. Authorities often focus on building houses on brownfield sites. Besides using such sites for permanent schemes such as housing, and temporary infrastructure such as playgrounds, car parks and open spaces (US EPA, 2019; Martinat, et al., 2018; Loures, et al., 2016; Florea, et al., 2013), brownfield development purposes can be diversified to incorporate renewables. Harvesting RE can bring positive impacts to the world by reducing our reliance on fossil fuels while simultaneously ensuring sustainable energy use.

The literature review also unveiled that developing brownfield land specifically for RE purposes was not a common practice in many countries. Most of the previous research concentrated on assessing the suitability of open sites (for example, desert, rural areas, offshore) for RE systems installations (Aly, et al., 2017; Jangid, et al., 2016; Kharseh, et al., 2015; Dolney & Flarend, 2013). Effectively, more criteria were considered in previous research, including the distance to substations, distance to the grid, distance to road, water bodies, urban areas and land cover.

Developing brownfield land for RE purposes offers many benefits including fewer consideration criteria due to brownfields' proximity to urban areas, more localised energy supply to areas with high energy demand, lower transmission loss and proximity to substations, grid connection and road networks. The development of brownfield land also enhances environmental sustainability through land reuse and the reducing carbon footprint of energy generation.

Section 2.4 identified challenges facing brownfield development due to many reasons including possible contamination and site ownership issues that leave brownfield sites to be untapped resources (Frantál, et al., 2015; Frantál, et al., 2013), but with the right policies and encouragements from various parties and authorities, brownfield sites can be redeveloped. Furthermore, these sites can often be utilised for RE purposes at a lower cost without needing remediation to meet environmental, health and safety standards (Limasset, et al., 2018; Bartke, 2011; Hamm & Walzer, 2007).

The review in Chapter 3 discussed the types of solar photovoltaic (PV) and wind turbines (WT) that can be installed at brownfield sites. Due to the different types of technologies and sizes of brownfield sites available, conventional horizontal axis wind turbine (HAWT) can be installed at large empty sites, whereas modern vertical axis wind turbine (VAWT) can be installed on buildings or at smaller sites. There are also VAWTs coupled with solar PV, such as the 712V Hybrid Aeroturbine, which is an ideal module for urban applications (Aerotecture, 2018). With this module, RE can be harvested throughout the day and would be useful to supply for the on-site ground source heat pump (GSHP) systems that can be connected to a district heating (DH) system.

Chapter 4 highlighted the various advantages of GSHP utilisation besides the reduced carbon emission to the environment. They can provide comfort to consumers with greater efficiency, the opportunity to utilise a mixture of RE sources alongside renewable heat (RH) and better-centralised heat production for both urban and suburban areas. With the advancement of DH systems, more renewable sources can be integrated into them, including recycled heat. The new generation of DH system concentrates on the use of low-temperature heating suitable for the incorporation of GSHP, as it is an ideal source for low-temperature DH systems.

It is advantageous for GSHP to be installed at brownfield sites dispersed in the developed/ urban areas, where the population density and heat demand are highest. The development can contribute to the increment of DH systems in Greater Manchester, as well as bringing brownfield land to better use. Policies practised in different countries to enhance their brownfield, RE and RH usage were reviewed in Chapters 2, 3 and 4. Many reasons were shown to encourage their growth, including environmental concerns and the availability of solar radiation. Authorities were also motivated to utilise brownfield land and harvest RE to stop climate change and its impacts on the Earth.

To boost the deployment of RE, public engagement is necessary to improve the awareness and willingness of the public to accept RE. From the policy review in Chapter 3, the most popular and reliable support for RE installations is the feed-in tariff (FIT). Implemented in 113 countries as of 2019, the FIT is recognisably the most effective incentive programme (REN21, 2020; Kylili & Fokaides, 2015; Park & Eissel, 2010; Pieters & Deltour, 1999). Although the system is no longer available in certain countries such as the UK and Denmark, the scheme is still available in other countries.

Pertaining to DH regulations, the existence of organisations such as the UK District Energy Association (ukDEA), the Danish District Heating Association (Dansk Fjernvarme) and the Swedish District Heating Association (Energiföretagen Sverige) is crucial in facilitating heat providers and their supply networks. They are also able to influence the regulations and promote the implementation of DH nationally with their members from various sectors.

In Chapter 5, this research reviewed available GIS models as a preliminary step to identify suitable models to aid spatial analysis. Suitable criteria relevant to solar PV and WT were then established to select feasible sites for the Greater Manchester context. This research then progressed to identify suitable brownfield sites for RE deployment in Chapters 6, 7 and 8. The results from the engagement with experts were fed into the spatial analysis. The tools used to prioritise brownfield sites were: 1) Spatial Analyst, to compute areal solar radiation in ArcGIS; 2) Workshops and AHP-OS, to elicit criteria weightings; and 3) ModelBuilder, to run iterative spatial analysis in ArcGIS.

For solar PV installations, aspect (azimuth) was considered to be a restrictive criterion, which acted as a preliminary brownfield site filter based on binary classification. Solar radiation, site size and flood risk level were categorised as evaluation criteria, where corresponding values for each criterion were rated. Slope, urban areas, protected areas and agricultural land were not considered as limiting criteria, as explained in section 7.4.

For WT installations, protected areas and airport areas were considered as restrictions due to the harm that WT pose to wildlife and the aviation system. Wind speed, slope and site size were considered as evaluation criteria. Agricultural land and urban areas, however, were not excluded from the site identification process. This was based on the theory that livestock farming would not be disturbed by turbines.

Brownfield sites that are close to urban areas make them attractive to developments because of that closeness. The proximity of such sites to grid connections or substations is another advantage as the connection to the distribution network will often be cheaper. Fewer criteria were considered in the selection of feasible sites. This was shown in Chapters 7 and 8, where fewer but more relevant criteria were used in identifying suitable sites.

To complete the spatial analysis process, the relevant evaluation criteria were weighted to determine their influence on feasible sites for development. The weightings were determined during a workshop involving experts in RE, RH and brownfield. They contributed their experience and subjective knowledge to the site identification, outlined in Chapter 6. Using multicriteria decision making (MCDM) and AHP-OS as a tool, the resultant weightings were gathered as numerical data and fed into the spatial analysis.

The results from pilot and MCDM workshops in Chapter 9 demonstrated that the Inverse Linear scale was the best scale for brownfield site identification as it provided final weightings with low dispersion and low consistency ratio. The AHP-OS shows how AHP has evolved from being a classic MCDM tool to a tool that can aggregate group ratings while simultaneously compute the consistency ratio and group consensus.

Apart from the Inverse Linear scale, AHP-OS also offers nine other scales that produce different sets of weightings, although using the same set of inputs. This acts as a ‘sensitivity analysis’ for brownfield site suitability, where different prioritisation results are obtained by using different scales. The set of weightings from this scale was then applied in the spatial analysis.

As documented in Chapter 9, brownfield sites received various final scores based on the interval class and criteria applicable to the technology considered. The scores were also influenced by the weightings of criteria obtained from multiple experts. Besides the weightings from the MCDM workshop, results achieved when applying weightings derived from the literature were also compared. This comparison was undertaken to examine the consistency and validity of the method to establish a transferable process model.

The results obtained from this research are useful for sustainable energy planning, where the utilisation of Spatial Analyst, MCDM workshop, AHP-OS and ModelBuilder was demonstrated as an effective way to select feasible brownfield sites for RE and RH development. With the implementation of the methods and the involvement of experts, Chapter 10 summarised the steps taken into a process model that can be adopted and applied in RE planning in other location to support the development of sustainable cities. Planners/decision makers can utilise the modifiable parameters in the process model in Figure 10.3 to substitute relevant parameters accordingly.

With the modifiable parameters set in the model, objectives, criteria and weightings can be altered to suit different project needs. The steps laid out in ModelBuilder can be executed to identify sites with development potential, accounting for relevant criteria. Once sites with development potential are identified, an in-depth site-specific analysis can be executed. The process model is also flexible in which experts can be involved while utilising an alternative MCDM method, for example, ELECTRE or Simple Added Weighting (SAW).

11.3 Research Key Contributions

This research expands the theoretical and practical discussions on brownfield development for RE and RH purposes in five ways:

➔ Study the potential of brownfield development and technologies installable on brownfield land.

The literature review highlighted various types of renewable technology deployable at brownfield sites, particularly solar energy, wind energy and ground heat energy. There are many types of solar panels, wind turbines and heat collectors with different capacities and capabilities in the market. With a large number of sites throughout Greater Manchester, this research explored the potential of brownfield redevelopment for the mentioned types of technology. The harvesting of RE can result in diversified brownfield usage, as well as increasing the RE share in the energy mix simultaneously contributing to sustainable cities with a low environmental impact.

➔ Exposed the limitation in existing the English planning policy.

Despite the current evolvement of policies in the UK and European countries, there was a lack of enforcement in terms of brownfield development beyond housing purposes. In the Planning Practice Guidance for Renewable and Low Carbon Energy which forms a part of the new National Planning Policy Framework (DCLG, 2015b; DCLG, 2013), there was an encouragement to utilise brownfield for RE installations. However, strict enforcement is not applied, causing complications in the policy and making the renewable share in the energy mix lower than other European countries such as Denmark and Sweden. The use of DH is also still at a low level throughout the UK.

➔ Established relevant criteria weightings for RE deployment on brownfield land using AHP-OS.

Selected criteria in Chapter 7 were weighted by experts with knowledge on brownfield, RE and the location of study. These qualifications were considered to recruit experts to contribute to suitable weightings. The experts' involvement was to avoid assigning arbitrary weightings to the criteria by a sole decision maker. By using AHP-OS, criteria were compared in pairs by experts to produce weightings for site identification, thus setting a set of criteria weightings that can be used in other brownfield development projects for RE.

➔ Identified feasible brownfield sites for RE and RH development in Greater Manchester.

Selected criteria implementable for RE and RH installations at brownfield sites were extracted from the literature, and the relevant criteria were applied in Greater Manchester. Although many solar radiation models were available for different GIS software, the Solar Analyst developed for ArcGIS was concluded to produce reasonable estimates of areal solar radiation for solar PV installation. The workshop held using the AHP technique contributed to practical criteria weightings, as it was able to enumerate decisionmakers' subjective judgement. The ModelBuilder tool aided the case analysis with the possibility of executing iterative processes in a few clicks. Suitable brownfield sites for RE and RH development in Greater Manchester were identified using the MCDM method in conjunction with ModelBuilder.

➔ Created an easy-to-adopt process model for RE projects with different objectives.

The process model created in Chapter 10 is a compilation of the methods adopted throughout this research combining with the guidelines by the Department for Communities and Local Government for RE site identification. Considering all the steps in the model, organisations, planners, and local authorities will be able to adopt it in other project planning to address different RE objectives. The model also offers users some flexibility and discretion to use different interval values and criteria weightings in its modifiable parameters. They can then follow the sequence set in the process model to find suitable sites without experimenting with multiple methods.

11.4 Research Objectives and How They Were Addressed

This research had an overarching goal to investigate the potential for brownfield land to contribute to the delivery of sustainable energy production. This goal was achieved by identifying suitable brownfield sites that can be developed for solar PV, WT and GSHP installations, using Greater Manchester as a case. The research also created a transferable process model applicable to other developments and geographical areas.

The first objective of this research was achieved through a systematic review of a wide range of literature in Chapters 2, 3 and 4 on what constitutes brownfield, what developments are associated with brownfield, the hindrance towards brownfield developments and types of RE technology installable on brownfield land. The second objective was addressed through policy review in Chapters 2, 3 and 4 to investigate how countries manage their brownfield land availability as well as advancing their RE and RH installations. This was done to understand how RE and RH can better penetrate the market and help governments achieve their zero-carbon goals.

The third objective was addressed through the involvement of experts in a workshop and the utilisation of AHP-OS to determine criteria weightings to identify the suitability of brownfield sites for different technologies, as outlined in Chapters 6, 7 and 8. Once the criteria weightings were obtained, they were used to achieve the fourth objective by using GIS, MCDM and expert decision making. These are presented in Chapter 9 as distributed score results and maps of prioritised brownfield sites.

The final objective of this research was achieved by summarising the steps executed in this research. Beginning with the initial step of objective setting to contribute to a sustainable city and ends with site suitability maps, the process model is transferable to project planning in other cities and countries, with parameters that can be modified.

11.5 Limitations

It is best to involve the local policymakers and planners to advocate this contextual study, so the Greater Manchester Combined Authority (GMCA) was approached for opinions on the criteria most important for site selection. Unfortunately, the GMCA did not have any expertise within their organisation, although creating a strategy to utilise their brownfield assets was in their plan. As a result, the GMCA could not contribute to this research and a contextual study was performed without any policy maker's involvement. Instead, other technical experts were invited to the workshop.

The number of participants in the MCDM workshop was small due to three reasons; 1) the small number of people with knowledge on the subject; 2) the small number of people with knowledge on the study area; 3) the smaller number of participants who turned up than registered. Although the number of responses was smaller than expected, it was used in the final MCDM rating as it was valid based on research using a small number of expert involvements for RE siting (Neufville, 2013). A high group consensus was still achieved from the workshop using the Inverse Linear scale due to its algorithm that provides a low criteria dispersion. The final results yielded justifiable brownfield priorities for RE installation.

This research adopted the use of AHP as the most suitable method to evaluate the technical and environmental data in the site selection. It is important to note that no one method can serve all purposes and contexts, so an appropriate MCDM method should be used to evaluate the criteria involved. While AHP has the ability to account for a variety of criteria demonstrated in this research, it has the risk of confusion when introduced to and used by non-experts due to the complexity of its pairwise comparison, as noted in Higgs (2006). This is the case when a large number of criteria is considered without any tool/software as an aid.

In terms of data, the thermal conductivity levels for superficial deposit were lacking, which posed a limitation on the site identification for GSHP. With the required data, a more comprehensive study could have been conducted to compare the type of GSHP to be prioritised for installation. From the limitations acknowledged in this thesis, future research can be executed to study the possibility of brownfield redevelopment for other types of RE adopting the process model proposed in Chapter 10, with the anticipation of better RE systems and sustainable cities in the future.

11.6 Recommendations

To achieve the main objective of this research to support sustainable city growth, brownfield utilisation was proposed for RE and RH harvesting. In previous studies that did not focus on specific sites, more criteria were used to evaluate the entire region/area. These include the distance to substations, distance to the grid, distance to road, water bodies, urban areas and land cover. Suitable brownfield sites, however, were identified using only relevant parameters, as elaborated in Chapter 7, to ensure the output gained from the technology is optimised. These are the basis of brownfield site identification for RE and heat purposes without involving the economic criteria. Accordingly, countries/regions with similar conditions (previously developed, close to substations/grid and road, sufficient fuel availability) can adopt those criteria in identifying feasible brownfield sites.

As part of the GIS analysis, the use of MCDM was ascertained to be advantageous for site identification analyses involving non-monetary criteria**.** The site evaluation using AHP offers the ability to compare the importance of criteria in pairs to determine their weightings. This method provides a more robust and reliable comparison as compared to applying a direct ranking method. Another advantage of AHP is the final consistency check, where a specific combination of pairwise comparisons can yield a consistency ratio of more than 0.1, making it invalid. As such, when using other MCDM methods in deciding the criteria weighting, the consistency ratio should also be monitored.

One tool applied in this research was the ModelBuilder, a plugin embedded in ArcGIS to support iterative analyses. As described in Chapter 6, ModelBuilder is capable of different workflows, either strings containing steps of inputs and tools, repetitive iterations or a combination of both. The former was applied in this research, where restriction and evaluation criteria were computed in separate analyses by changing their weightings and other parameters. Utilising ModelBuilder reduces execution time as similar analyses with different values can be run more conveniently. This is particularly advantageous in performing sensitivity analyses. If there are changes in the regulations and planning policy requiring thresholds to be revised, or if policymakers, community or experts change their preferences towards any criteria, all the changes can be easily incorporated in ModelBuilder.

The process model compiled at the end of this research allows for the methods applied in this research to be replicated in other places to aid the site identification process for other purposes. By utilising the process model, users can adapt the functions embedded in the model to suit their goal and objectives. As exemplified in this research, the land reuse (or brownfield utilisation) aspect was chosen to be combined with RE installation to address the gap identified in the literature. Subsequently, when users want to address any gap through their project, the objectives can be changed accordingly. By using this process model, users will be able to identify relevant data to be used more conveniently. The modifiable parameters also allow users to make necessary adjustments for their sensitivity analysis, for instance, using different criteria weightings and interval values. In short, the process model provides a 'shortcut' of methods and steps to follow, where the applicability of the process is not geographically limited.

11.7 Future Research

The research on which this thesis outlined was limited to certain resources. To account for various technical and geographical criteria, MCDM was used to investigate the potential of brownfield. Apart from MCDM, other approaches can be used to select suitable sites, for example, cost-benefit analysis. In this research, the MCDM was adopted to better accommodate the environmental criteria for GIS through qualitative analysis. However, future research investigating similar geographical location or conditions can adopt a non-MCDM approach to compare the results.

The technologies focussed upon in this research were the standard solar panels, conventional HAWT and urban VAWT due to the variety of brownfield size available in Greater Manchester. Although some brownfield sites can host large HAWT, in urban spaces where HAWTs are not practical, solutions such as VAWT can instead be deployed. However, the use and installation of VAWT were not studied in detail as they were was beyond the scope of this research. It would be a good focus for future research to comprehensively examine the use of urban VAWT at brownfield sites to benefit cases/regions with extreme wind conditions.

Due to the limitation of thermal conductivity data, the site prioritisation for GSHP installations was only done for bedrock, which is suitable for borehole heat collectors. If the thermal conductivity level was available for superficial deposits, analysis for trench type of GSHP would be feasible. Future research can compare the feasibility of different types of GSHP and prioritise different type for different sites using the process model in Chapter 10.

Regarding trench GSHP, a type of heat collector that was not addressed in this research was the 'slinky' type. This loop type of heat collector has a better energy yield from the same ground type when compared to the horizontal trench heat collector. The use of slinky coils for GSHP systems can be an option if the space factor permits, as the installation cost is lower than the borehole collector, but the coefficient of performance is higher than the horizontal heat collector. This can be a potential focus for future research to involve brownfield and district heating energy generation.

This research can also be expanded with the creation of an online toolkit for stakeholders and practitioners as an aid in identifying potential sites that they wish to evaluate. This toolkit would provide a preliminary evaluation in a broader context as conducted in this research. Furthermore, future research can engage with planners and/or local authorities, for example, Greater Manchester Combined Authority to investigate how they would use the toolkit and research findings and how it can be generalised to work for other contexts.

To complement the research findings, further study may also look at identifying challenges that local authorities face in redeveloping brownfield sites in different cities/regions including in the southern hemisphere and to identify suitable sites for RE placement. This would inform researchers on the way to move forward in tackling brownfield and RE issues in a broader context.

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Appendix A

Urban Wind Turbine Regulations

Generally, In the UK, the installation, alteration or replacement of a building-mounted wind turbine can be considered as permitted development provided the conditions set by the government are met (Energy Saving Trust, 2018; Planning Portal, 2018):

1. Permitted development rights only apply for installation of building-mounted turbines on detached houses and other detached buildings within the compound of a house or block of flats. This must not include flats that also contain commercial premises. For installation on top of flat roofs, planning permission is required. Additionally, development is only permitted if the WT installation complied with the Microgeneration Certification Scheme Planning Standards (MCS 020).
2. The permitted development right is only granted for the first WT installation, with the condition there is no air source heat pump (ASHP) installed at the property. Further installation of WT or ASHP requires planning permission.
3. No installation is allowed on safeguarded land.
4. No part of the WT including the blades should extend more than 3m beyond the highest part of the roof or exceed an overall height of 15m, including the building, hub and blade.
5. The distance between the ground level and the lowest part of the blade must be more than 5m, and no part of the WT can be within 5m of any boundary.
6. The swept area of any building-mounted WT blade must be less than $3.8m^2$.
7. In Conversation Areas, installation is not permitted if the installation would face a highway.
8. Permitted development rights do not apply to a WT within the curtilage of a Listed Building or on designated land.
9. The WT blades must be of non-reflective material.
10. To be eligible for the Feed-in-Tariff, the installer and the WT used must be both certified under the Microgeneration Certification Scheme (MCS).

A general guidance set by the Ministry of Housing, Communities & Local Government (2015) states that the fall over distance (i.e., the height of the WT to the tip of the blade) + 10% is often used as a safe separation distance. However, this value is often less than the minimum desirable distance between the WT and the occupied buildings. It is noteworthy that this only applies to the HAWT where the tip can have a distance to the building rooftop and not the VAWT where the turbine sits as a cylinder.

Appendix B

Physical Parameter

The solar altitude (α) and azimuth (a_s) angles are related to the latitude, solar declination (δ_s) and hour angle (h_s) as described in the equation by Kreith and Kreider (1978):

$$\sin\alpha = \sin L \sin\delta_s + \cos L \cos\delta_s \cos h_s \quad \text{(B-1)}$$

$$\sin a_s = \cos\delta_s \sin h_s / \cos\alpha \quad \text{(B-2)}$$

where L is the latitude of the site.

The r.sun Model

For direct solar radiation, it can be estimated using Bouger's Law for a simplified case as illustrated in (B-3):

$$I_b = I_o e^{-kM} \quad \text{(B-3)}$$

with the assumption of clear sky, I_b and I_o are the terrestrial and extra-terrestrial intensities of beam radiation, k is an absorption constant and M is the air mass ratio. M varies from 1 to 30 corresponding to when the sun is above the head and when it is at the horizon. M value is proportional to sec ψ, or $1/\cos\,\psi$, which is the zenith angle (Gates, 1980).

Using Gates (1980) formula, diffuse radiation (I_d) can be computed using:

$$I_d = I_o \tau_d \cos^2\beta/2 \sin\alpha \quad \text{(B-4)}$$

with τ_d as the radiation diffusion coefficient, α and β as solar altitude angle and tilt angle of the surface (slope), respectively. Gates (1980) suggested that the typical values of direct beam transmittance for a dust-free clear sky range between 0.400 and 0.800, with the corresponding diffuse transmission range between 0.153 and 0.037.

In another explanation by Ruiz-Arias, et al. (2009), the diffuse radiation on a horizontal surface I_{Dh} is estimated as the product of the normal extra-terrestrial irradiance I_{0n}, a diffuse transmission function T_n and a diffuse solar altitude function F_d (dependent on solar altitude α, in the function (Hofierka & Suri, 2002)

$$I_{Dh} = I_{0n} T_n(T_L) F(\alpha) \quad \text{(B-5)}$$

Using an isotropic assumption, the diffuse radiation is given by (Dubayah & Rich, 1995; Dozier & Frew, 1990):

$$V_d \bar{F} \downarrow (\tau_0) \quad \text{(B-6)}$$

where $\bar{F} \downarrow (\tau_0)$ is the average diffuse radiation on a level surface at a certain elevation, and V_d varies from 1 (clear) to 0 (completely obstructed). Differently, the instantaneous diffuse radiation (in W/m^2) for a point on a surface with slope α and azimuth β_0 is given by:

$$I_{DI} = E_d^h x \frac{\left(\int_{-\pi}^{\pi} d\theta \int_{h(\theta)}^{\frac{\pi}{2}} (\sin a \cos h \cos(\theta - \beta_0) + \cos a \sin h \cos h \, dh \right)}{\pi} \quad \text{(B-7)}$$

where E_d^h is the instantaneous diffuse radiation on a horizontal surface, *h(θ)* is the horizon angle in the azimuth direction of *θ*. *Π* is used as a normaliser for the radiation on a horizontal surface facing the sky with no obstruction (Dozier & Frew, 1990). Note that the integration part of the multiplier is the SVF which is simplified by Kumar et al. (1997) in their model to be $\cos^2 a/2$ with a as the slope of an infinitely long slope of a surface.

For reflected radiation, by assuming that the reflection component is isotropic, and V_d for an infinitely long slope is (1+ cos S)/2, C_t can be approximated to

$$C_t \approx \frac{1 + \cos S}{2} - V_d \quad \text{(B-8)}$$

to give reflected radiation from the surrounding terrain to be:

$$C_t \bar{F} \uparrow (\tau_0) = C_t R_0 \bar{F} \downarrow (\tau_0) \quad \text{(B-9)}$$

with $\bar{F} \uparrow (\tau_0)$ being the amount of radiation reflected off the surface with an average reflectance of R_0.

The Solar Analyst Model

In terms of parameterisation, SA has a simpler one which models atmospheric effects based on atmospheric transmissivity and air mass depth;

$$\tau = \tau_s{}^{m(\beta)} \quad \text{(B-10)}$$

where τ_s is the transmissivity of the atmosphere on the shortest path which is the direction of zenith, and $m(\beta)$ is the relative optical path length, which is a function of zenith angle and elevation (Fu & Rich, 1999).

In SA, the direct solar insolation from a sun map sector $I_B^{Z,\psi}$ with centroid at zenith angle Z and azimuth angle ψ is computed using

$$I_B^{Z,\psi} = I_S \tau^m ST^{Z,\psi} SG^{Z,\psi} \cos\theta^{Z,\psi} \quad \text{(B-11)}$$

where I_s is the solar constant, τ is the direct atmospheric transmissivity, m is the relative optical path length, $ST^{Z,\psi}$ is the time duration in the sky sector, $SG^{Z,\psi}$ is the non-obstructed gap fraction for the sun map sector and $\theta^{Z,\psi}$ is the angle of incidence between the centroid of the sky sector and the axis normal to the surface (Fu & Rich, 2000).

For each sky sector, the diffuse radiation at its centroid is calculated as $I_D^{Z,\psi}$, integrated over the time interval (T) and corrected by the sky gap fraction $SKG^{Z,\psi}$ and angle of incidence $\theta^{Z,\psi}$ using the equation

$$I_D^{Z,\psi} = I_{Gn} P_D T \, SKG^{Z,\psi} \mathrm{W}^{Z\Psi} \cos\theta^{Z,\psi} \quad \text{(B-12)}$$

with I_{Gn} as the global normal radiation calculated by summing the direct radiation from all the sectors without correction for angle of incidence, and then using 1-P_D to correct the proportion of direct radiation. P_D is the proportion of global normal radiation flux that is diffuse and $\mathrm{W}^{Z\Psi}$ is the proportion of diffuse radiation in a given sky sector.

In SA, a uniform sky diffuse model is used, and $\mathrm{W}^{Z\Psi}$ is calculated as:

$$\mathrm{W}^{Z\Psi} = \frac{\cos Z_1 - \cos Z_2}{N_\psi} \quad \text{(B-13)}$$

Z_1 and Z_2 are the bounding zenith angles of the sky sector, and $N\psi$ is the number of azimuth divisions in the skymap (Fu & Rich, 2000).

Another way of calculating the diffuse radiation is based on the direct radiation as explained (B-14):

$$E_d^h = \left(\frac{R_{dir}}{1 - P_{dif}}\right) x P_{dif}; \;\; R_{dir} = I_0 \tau \cos z \quad \text{(B-14)}$$

with R_{dir} as instantaneous direct radiation and $\left(\frac{R_{dir}}{1-P_{dif}}\right)$ as global normal radiation. P_{dif} is the diffuse coefficient, I_0 is the solar constant and τ is the instantaneous atmospheric transmittance and z is the solar zenith angle.

Sky view factor (SVF) is computed by taking the diffuse incidence angle at the centre of any sector i as λ_i, the surface area of the sector on the hemisphere as A_i, number of sky sectors as N_s, the proportion of the unobstructed sector i as SG_i (ranging between 0 and 1, with 0=completely blocked and 1=clear sky):

$$SVF = 1/\pi \sum_{i=1}^{N_s} \cos \lambda_i \, A_i SG_i \qquad \text{(B-15)}$$

If azimuth divisions are assumed to be N_a, A_i can be calculated as

$$A_i = \frac{2\pi(\cos \theta_{iu} - \cos \theta_{il})}{N_a} \qquad \text{(B-16)}$$

where θ_{iu} and θ_{il} are upper and lower bounding zenith angles of the sky sector i, respectively. By substituting Equation (B-16) into (B-15) this yields SVF as:

$$SVF = 2 \sum_{i=1}^{N_s} \cos \lambda_i \, SG_i \, \frac{(\cos \theta_{iu} - \cos \theta_{il})}{N_a} \qquad \text{(B-17)}$$

SVF, under an isotropic diffuse radiance assumption, can be calculated using Equation (B-17).

Appendix C

Full buffer zones for wind energy as guidance (DCLG, 2014; Sliz-Szkliniarz & Vogt, 2011; Aydin, et al., 2010; Nguyen, 2007; General Directorate of Civil Navigation, 2007; Environment Foundation of Turkey, 2006; Yue & Wang, 2006; Tester, et al., 2005; Turkish Government, 2005; Hansen, 2003; Baban & Parry, 2001; Voivontas, et al., 1998; Turkish Government, 1994; Brower, 1992; Clarke, 1991):

Zone	Distance (m)
Nature monuments	100
Roads	100
Railway lines	100
Mine and dump areas	100
Coastline	100
Power network	200
Flood area	200
Forest	200
Industrial areas	250
Streams and inland water	250
Bird habitat and bird migration pathway	300
Leisure park and recreational areas	450
Protected forest	500
Areas of special protection of habitats	500
Single dwellings	500
Wildlife conservation areas	500
Noise avoidance	500
Towns	1000
Historic and National Trust properties	1000
Castle and cultural derelict	1000
Areas of special protection of birds	1000
Urban areas	2000
Settlements	2000
Ecologic and topographic features	2500
Airport	3000
Habitat of migrating birds	5000

Appendix D

AHP Software Comparison

Software	Price	Trial/Student price	Advantages (attributes)	Disadvantages
AHP-OS	£0	Free to use	Online, simple to use, a consistency check is done before user submit, ability to use different types of scales,	No built-in sensitivity analysis.
Expert Choice/ Comparion	USD 900/ year	No trial, only student price	Online, intuitive, widely used by organisations and government bodies, participants can be invited directly from the 'project management' page, built-in sensitivity analysis, no availability of different scales, no open access so not transparent.	No trial, only demo if you are serious about buying.
Transparent Choice	USD 1500/ year	Trial available, up to 2 evaluators, student price available	Online, average group score is aggregated using geometric method, comments and consistency check can be added while rating, disagreements can be analysed on the software, voting analysis can be done per comparison.	No transitivity rule application.
SpiceLogic	USD 49		Downloadable software, used by government bodies, a consistency check is done while rating and marked in red, option to enforce transitivity rule for a large number of comparison (suitable for many criteria), sensitivity analysis is live while rating.	Unable to collect multiple decisions for groups. Graphical, but difficult to understand the comparison.
SuperDecisions	£0	Free to use.	Downloadable software, sensitivity analysis can be done.	Use ratings model, have to build clusters and node, tutorial not comprehensive,

				not suitable for group decision making.
HIPRE	£0	Free to use online version.	Java-based applet, cloud-based.	Only have 1-9 and balanced scale, big learning curve, not straight forward to build hierarchy and collect group decision.
EasyAHP	€99		Online-based	Too simple, no good feature or documentation on the computation, not suitable for professional.

Appendix E

AHP-OS Scales

Scale name	Scale function	*M*	Maximum number of criteria
Linear AHP scale	$c = x$	9	10
Logarithmic scale	$c = \log_a(x + a - 1)$	3.3	4
Root square scale	$c = \sqrt[a]{x}$	3	4
Inverse linear scale	$c = \frac{9}{10 - x}$	9	10
Balanced scale	$c = \frac{0.45 + 0.05x}{1 - 0.45 + 0.05x}$	9	10
Balanced-n scale	$w_{bal} = \frac{1}{n} + \frac{w_{max} - \frac{1}{n}}{M - 1}(x - 1)$ $c = \frac{w_{bal}}{1 - w_{bal}}(n - 1)$	9	10
Adaptive-balanced scale	Same as Balanced-n, with w_{max} =0.9	$M^*=M(n\text{-}1)$	-
Adaptive scale	$c = x^{1+\frac{\ln(n-1)}{\ln 9}}$	$M^*=M(n\text{-}1)$	-
Power scale	$c = x^2$	81	82
Geometric scale	$c = a^{x-1}$	256	257

x is the value on the integer judging scale for pairwise comparisons from 1 to 9. *c* is the ratio used as entry into the decision matrix, *M* is the maximum value of *c* for *x*=9. A more comprehensive discussion on the differences of scale functions is available in Goepel (2019).

Table is based on Goepel (2019).

Appendix F

AHP Pairwise Summary – Scenario 1 for Solar PV

Criteria Comparison

	Solar radiation	Flood zone	Site size
Solar radiation	1.00	7.00	5.00
Flood zone	0.143	1.00	0.33
Site size	0.20	3.00	1.00
Column Sum	**1.34**	**11.00**	**6.33**

Normalised Criteria

	Solar radiation	Flood zone	Site Size	Row Sum	Average Score/ Weighting (Sum/3)	Weighting %
Solar radiation	0.74	0.64	0.79	2.17	0.72	72.35
Flood zone	0.11	0.09	0.05	0.25	0.08	8.33
Site size	0.15	0.27	0.16	0.58	0.19	19.32
Total	**1.00**	**1.00**	**1.00**	**3.00**	**1.00**	**100.00**

Consistency Check

Solar radiation	3.14
Site size	3.01
Flood zone	3.04
Sum	9.20

No. of Criteria	3
Average Consistency	3.07
Consistency Index (CI)	0.03
Random Index (RI)	0.58
Consistency Ratio (CI/RI)	0.06
Consistent? (<0.1)	Yes

Random Index

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

AHP Pairwise Summary – Scenario 2 for Solar PV and Wind Turbine

Criteria Comparison

	Solar radiation/ wind speed	Flood zone/slope	Site size
Solar radiation/ wind speed	1.00	2.00	2.00
Flood zone/slope	0.50	1.00	1.00
Site size	0.50	1.00	1.00
Column Sum	**2.00**	**4.00**	**4.00**

Normalised Criteria

	Solar radiation/ wind speed	Flood zone/ slope	Site Size	Row Sum	Average Score/ Weighting (Sum/3)	Weighting %
Solar radiation/ wind speed	0.50	0.50	0.50	1.50	0.50	50.00
Flood zone/slope	0.25	0.25	0.25	0.75	0.25	25.00
Site size	0.25	0.25	0.25	0.75	0.25	25.00
Total	**1.00**	**1.00**	**1.00**	**3.00**	**1.00**	**100.00**

Consistency Check	
Solar radiation	3.00
Site size	3.00
Flood zone	3.00
Sum	9.00

No. of Criteria	3
Average Consistency	3.00
Consistency Index (CI)	0.00
Random Index (RI)	0.58
Consistency Ratio (CI/RI)	0.00
Consistent? (<0.1)	Yes

Random Index

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

AHP Pairwise Summary – Scenario 3 for Solar PV and Wind Turbine

Criteria Comparison

	Solar radiation/ wind speed	Site size	Flood zone/ slope
Solar radiation/ wind speed	1.00	7.00	5.00
Site size	0.143	1.00	0.33
Flood zone/slope	0.20	3.00	1.00
Column Sum	**1.34**	**11.00**	**6.33**

Normalised Criteria

	Solar radiation/ wind speed	Site Size	Flood zone/ slope	Row Sum	Average Score/ Weighting (Sum/3)	Weighting %
Solar radiation/ wind speed	0.74	0.64	0.79	2.17	0.72	72.35
Site size	0.11	0.09	0.05	0.25	0.08	8.33
Flood zone/slope	0.15	0.27	0.16	0.58	0.19	19.32
Total	1.00	1.00	1.00	3.00	1.00	100.00

Consistency Check

Solar radiation/ wind speed	3.14
Site size	3.01
Flood zone/ slope	3.04
Sum	9.20

No. of Criteria	3
Average Consistency	3.07
Consistency Index (CI)	0.03
Random Index (RI)	0.58
Consistency Ratio (CI/RI)	0.06
Consistent? (<0.1)	Yes

Random Index

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

AHP Pairwise Summary – Scenario 1 for Wind Turbine

Criteria Comparison

	Wind speed	Slope	Site size
Wind speed	1.00	9.00	7.00
Slope	0.11	1.00	0.33
Site size	0.14	3.00	1.00
Column Sum	**1.25**	**13.00**	**8.33**

Normalised Criteria

	Wind speed	Slope	Site size	Row Sum	Average Score/ Weighting (Sum/3)	Weighting %
Wind speed	0.80	0.69	0.84	2.33	0.78	77.66
Slope	0.09	0.08	0.04	0.21	0.07	6.85
Site size	0.11	0.23	0.12	0.46	0.15	15.49
Total	1.00	1.00	1.00	3.00	1.00	100.00

Consistency Check

Solar radiation/ wind speed	3.19
Site size	3.01
Flood zone/ slope	3.04
Sum	9.25

No. of Criteria	3
Average Consistency	3.08
Consistency Index (CI)	0.04
Random Index (RI)	0.58
Consistency Ratio (CI/RI)	0.07
Consistent? (<0.1)	Yes

Random Index

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Appendix G

MCDM workshop responses

Answers for question 4, “Why do you rate the criteria importance in such a way?”:

1. Site size has the highest influence on the output generated and the cost for a solar farm
2. Solar radiation is around the same level across GM, so not that important to consider as compared to site size
3. Flood areas won’t usually be developed or there will be a protection to defend them or infrastructure can be installed with preventative measures, so they get low importance
4. Wind speed has higher variation, and can work in isolation, so it requires higher priority than site size
5. Flood zones are prioritised as energy is needed, so projects should still be executed in flood areas with defence
6. Solar radiation is the most important as it affects the output generated
7. Flood zones are more important to consider after solar radiation and before site size, as a severe flood impact can damage the solar panels and the associated electronics
8. For wind turbine consideration, the slope is more important than the site size as it influences the feasibility and safety of the installation
9. Site size is least important for wind turbines as vertical urban wind turbines do not require a large area
10. Solar radiation and wind speed are the most important parameters as they directly influence the solar and wind power output
11. Flood zone is more important to consider than site size, as solar panels and wind turbines should not be installed in flood areas, although they can take a small space to install
12. Flood zone is the least important as there are not many sites in GM that are located in such areas, and there are ways to mitigate the problem
13. Slope received the lowest importance as most of the areas in GM are flat

Answers for question 6, “What other criteria do you think should also be considered?”:

1. Cost of development (£/kWp output) (2 count)
2. Land value
3. Ecological impacts
4. Distance to population centres (2 count)

5. Size of demand
6. Type of technology
7. Resource availability
8. Site conditions
9. Wind direction for wind installation
10. Temperature elevation for solar installation
11. Wind tunnel and wake recovery around wind turbines
12. Neighbouring buildings for solar sites

Appendix H

Iterative steps used in ModelBuilder

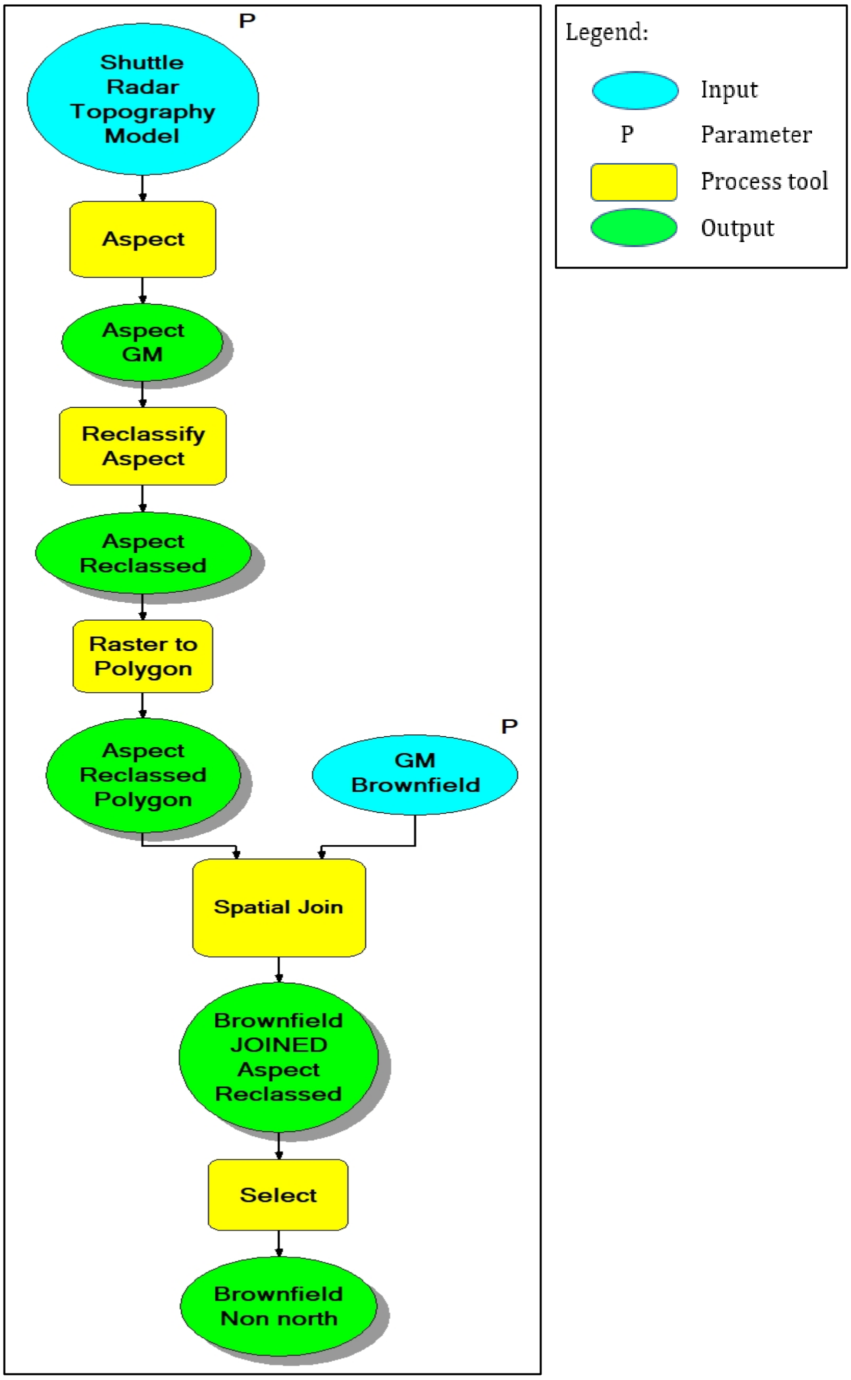

Figure H.1.1: Solar PV restriction model built-in ArcGIS ModelBuilder.

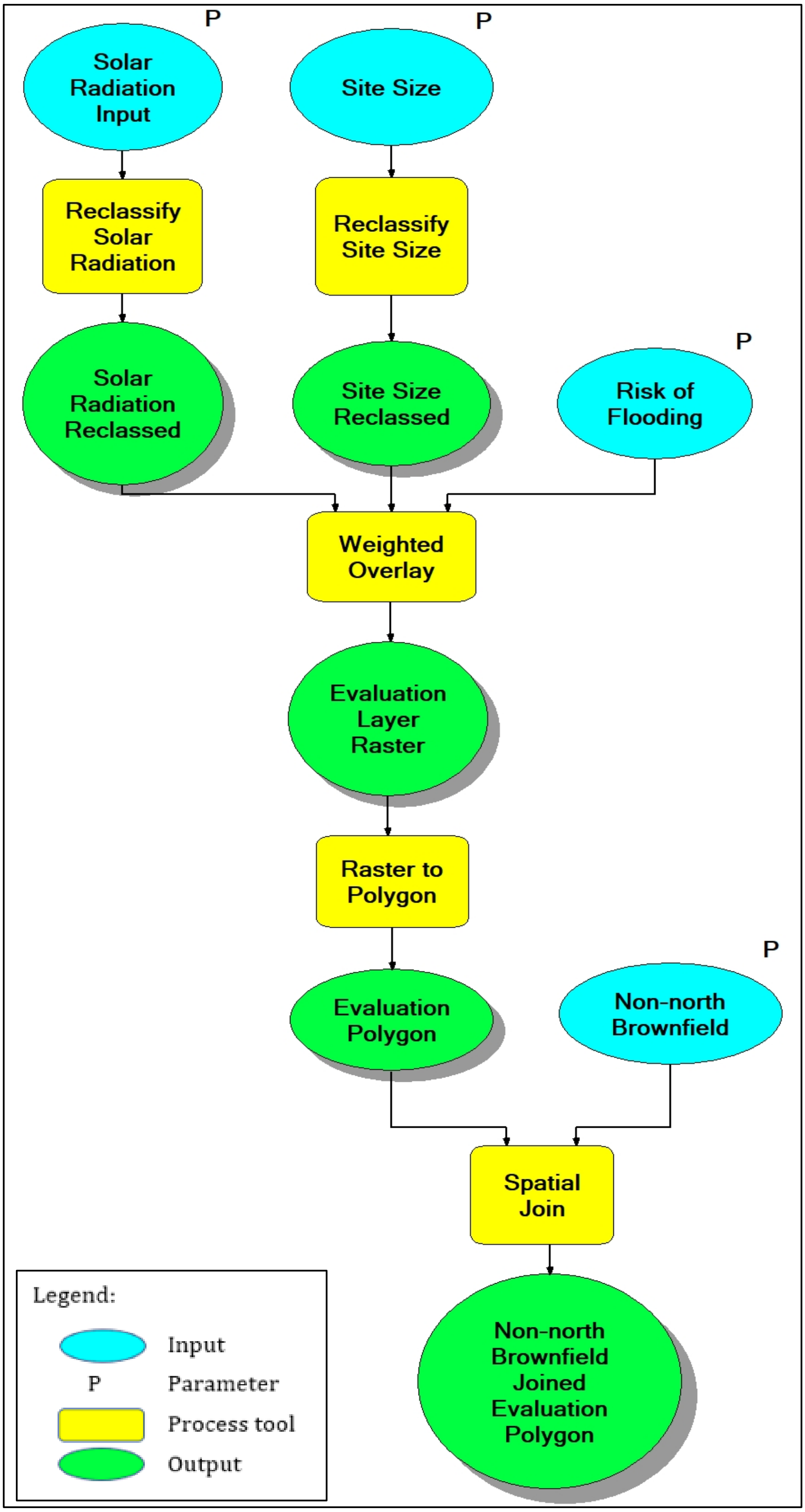

Figure H.1.2: Solar PV evaluation model.

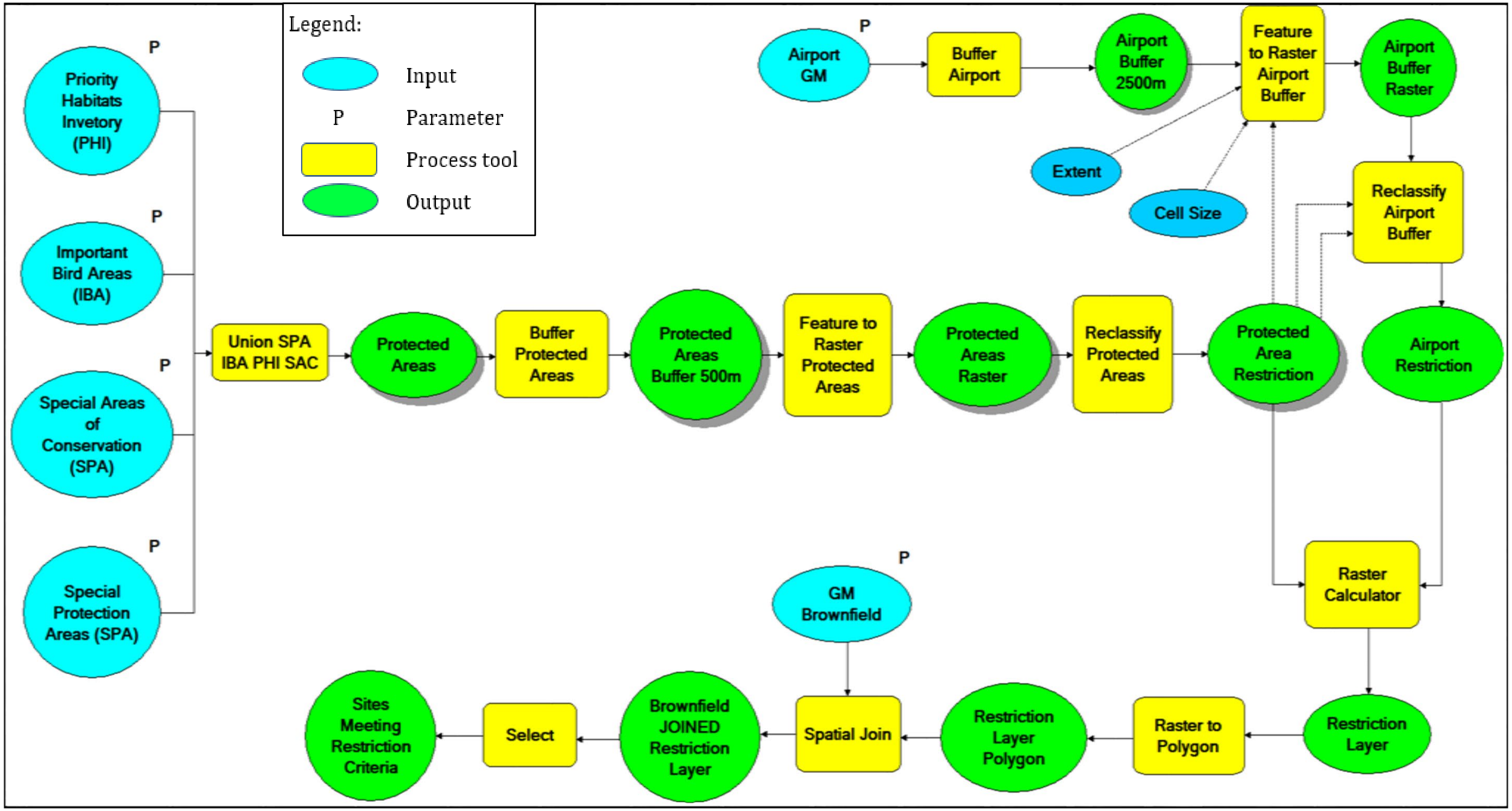

Figure H.1.3: Elimination process for wind energy on ModelBuilder.

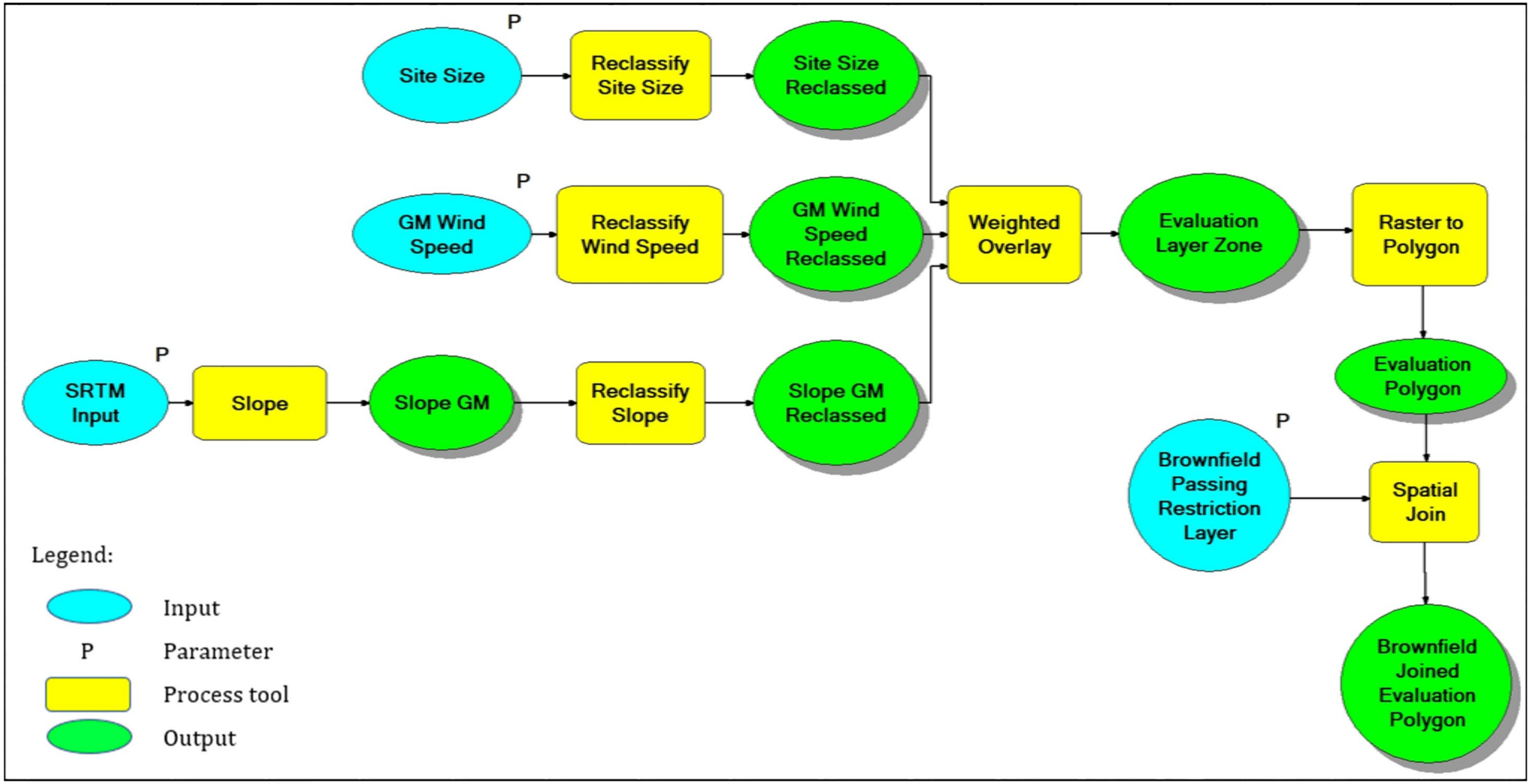

Figure H.1.4: Wind turbine evaluation model.

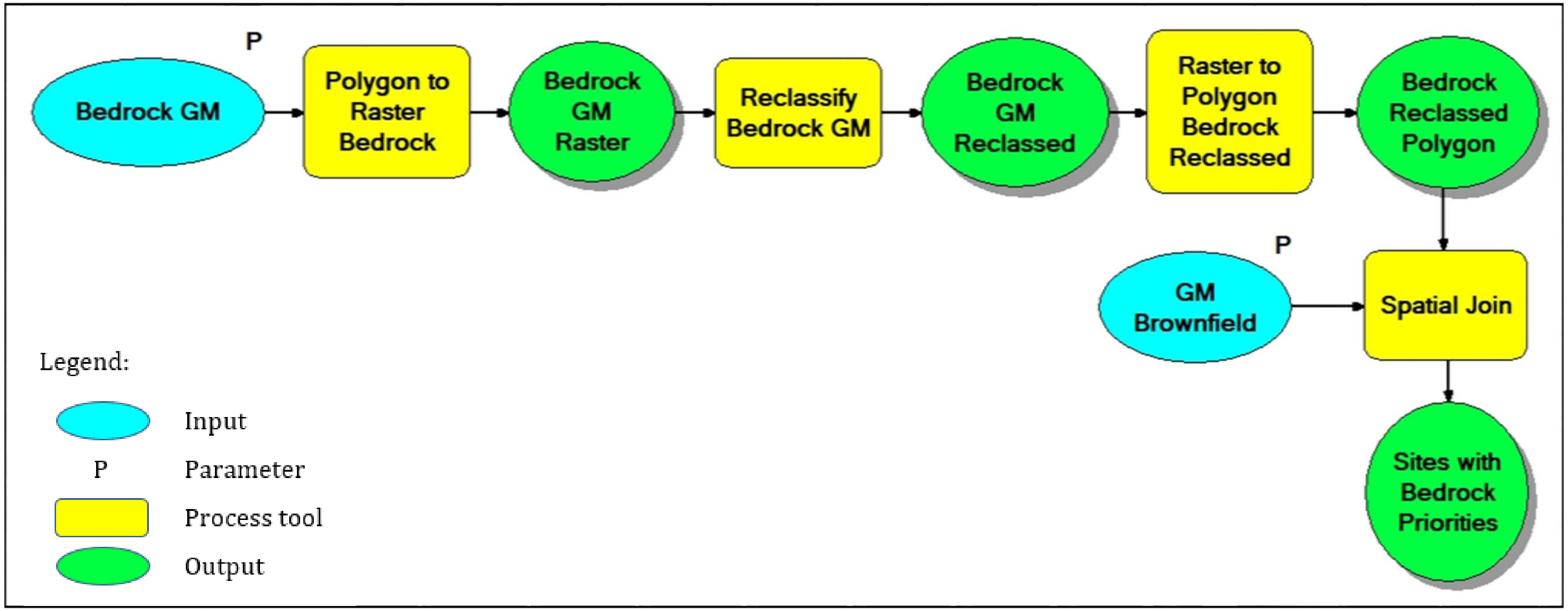

Figure H.1.5: Steps for bedrock classification.

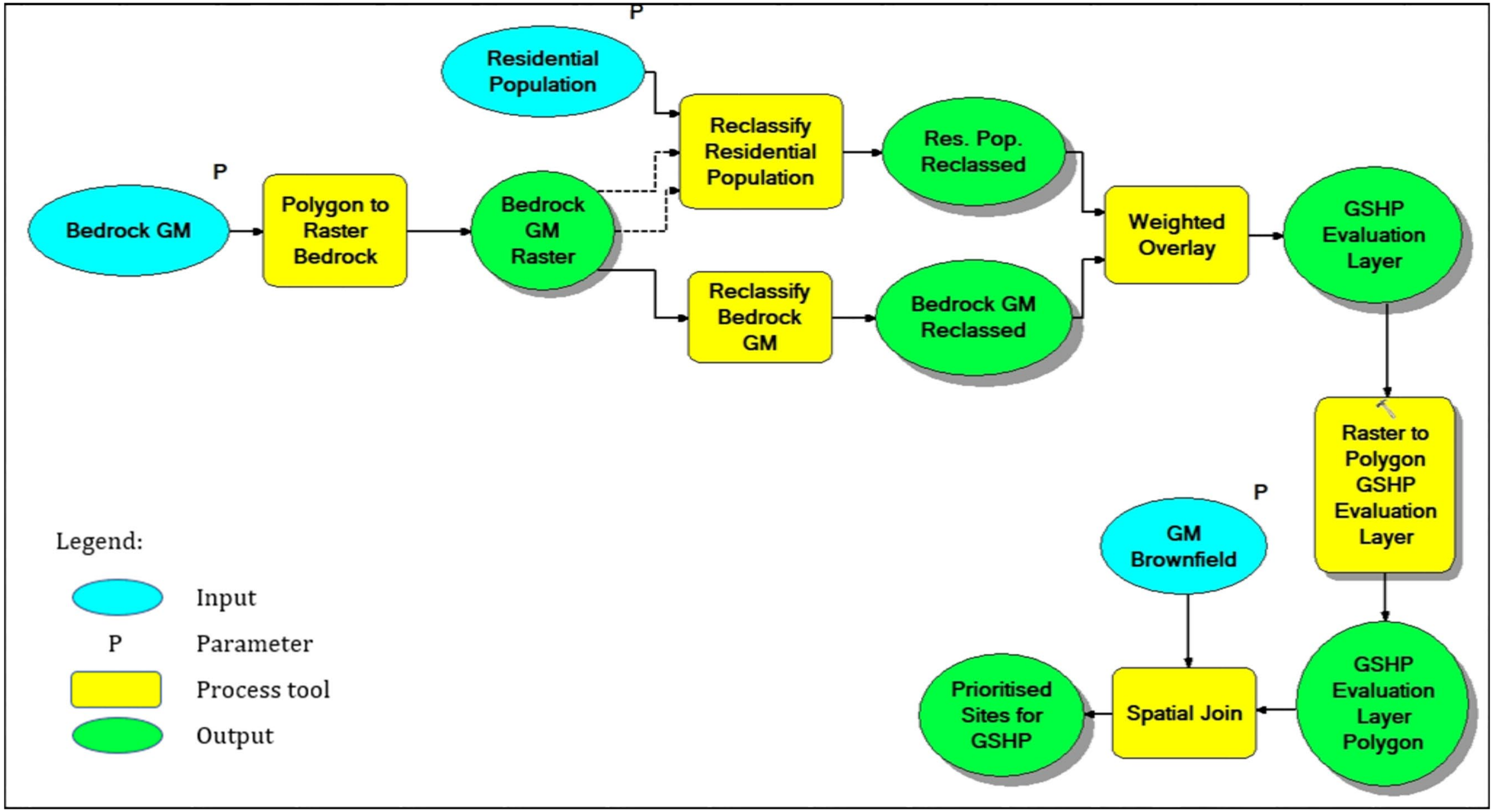

Figure H.1.6: Preliminary steps in identifying suitable sites for a GSHP system based on bedrock priorities and residential population size.